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Source Assessment: Residential Combustion of Coal

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Coal	Hydrocarbons	Residential Heating	21D	07C
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PREFACE

The Industrial Environmental Research Laboratory (IERL) of the U.S. Environmental Protection Agency (EPA) has the responsibility for insuring that pollution control technology is available for stationary sources to meet the requirements of the Clean Air Act, the Federal Water Pollution Control Act, and solid waste legislation. If control technology is unavailable, inadequate, or uneconomical, then financial support is provided for the development of the needed control techniques for industrial and extractive process industries. Approaches considered include: process modifications, feedstock modifications, add-on control devices, and complete process substitution. The scale of the control technology programs ranges from bench- to full-scale demonstration plants.

The Chemical Processes Branch of the Industrial Processes Division of IERL has the responsibility for programs to develop control technology for a large number of operations (more than 500) in the chemical industries. As in any technical program, the first question to answer is, "Where are the unsolved problems?" This is a determination which should not be made on superficial information; consequently, each of the industries is being evaluated in detail to determine if there is, in EPA's judgment, sufficient need for emissions reduction. This report contains the data necessary to make that decision for the air emissions from the residential combustion of coal.

Monsanto Research Corporation has contracted with EPA to investigate the environmental impact of various industries which represent sources of pollution in accordance with EPA's responsibility as outlined above. Dr. Robert C. Binning serves as Program Manager in this overall program, entitled "Source Assessment," which includes the investigation of sources in each of four categories: combustion, organic materials, inorganic materials, and open sources. Dr. Dale A. Denny of the Industrial Processes Division at Research Triangle Park serves as EPA Project Officer. In this study of the residential combustion of coal, Dr. Ronald A. Venezia served as EPA Task Officer.

ABSTRACT

This report summarizes the assessment of air emissions from the residential combustion of coal and includes some discussion of solid residues and the leaching of these materials. The report covers anthracite, bituminous, and lignite coals, with primary emphasis on bituminous coals because they represent approximately 70% of residential coal combustion.

Approximately 2.6 million metric tons of coal were burned as a primary source of heat in an estimated 493,018 housing units in 1974. Geographical distribution of coal-fired heating devices is related to the location of major coal fields. States in the Appalachian coal region account for 72% of the residential combustion units burning bituminous coal. Homes burning anthracite are confined to Pennsylvania and the east coast, while those burning lignite are located in North Dakota. From 1974 to 1975 residential coal usage increased by 50% in the West and declined 25% in the remaining regions.

Stoker-fed boilers and warm-air furnaces are currently being marketed for burning coal as a primary source of heat in residential structures; however, hand-fed units and room heaters also exist. Emissions from these units include particulates, sulfur oxides, nitrogen oxides, carbon monoxide, hydrocarbons, polycyclic organic material (POM), and trace elements. The severities of these emissions were assessed for an average source. Emissions of POM's were found to have a severity of 2.6 for combustion of bituminous coal while the remaining emissions had severities of 0.05 or less.

A special assessment of the environmental impact of an array of 100 houses burning coal indicates the potential for a thirtyfold increase in the severities of associated emissions. In this case, the severities were greater than 0.05 for 16 individual elements and 4 criteria pollutants; severities were 91 and 1.7 for POM in bituminous and anthracite coal burning, respectively.

This report was submitted in partial fulfillment of Contract No. 68-02-1874 by Monsanto Research Corporation under the sponsorship of the U.S. Environmental Protection Agency and covers the period November 1976 to November 1978.

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ABBREVIATIONS AND SYMBOLS

A_R	--$Q/ac\pi u$
a,b,c, d,f	-- constants (Appendix E)
B_R	-- $-H^2/2c^2$
C, D	-- atmospheric stability classes
e	-- 2.72
F	-- hazard factor, g/m^3
H	-- emission height, m
Nm^3	-- volume in cubic meters at standard conditions (i.e., 0°C and 1 atm)
PCB	-- polychlorinated biphenyl
POM	-- polynuclear organic material
ppm	-- parts per million
Q	-- emission rate, g/s
Q_i	-- emission rate for species i, g/s
Q_o	-- emission rate of reference species, g/s
S	-- source severity
t	-- averaging time, min
t_o	-- short-term averaging time of 3 min
u	-- national average wind speed, 4.5 m/s
$\bar{u}$	-- average wind speed, m/s
V_1	-- stack gas volume during ON segment of heating cycle, m^3
V_2	-- stack gas volume during OFF segment of heating cycle, m^3
x	-- downwind dispersion distance from source of emission release, m
x_1, x_2	-- distance from the source where $\overline{\chi}/F$ equals 1.0 or 0.05, m
y	-- horizontal distance from centerline of dispersion, m
π	-- 3.14

ABBREVIATIONS AND SYMBOLS (continued)

σ_y -- standard deviation of horizontal dispersion, m

σ_z -- standard deviation of vertical dispersion, m

χ -- downwind ground level concentration at reference coordinate (x, y), g/m^3

$\bar{\chi}$ -- time-averaged ground level concentration, g/m^3

χ_{max} -- maximum ground level concentration, g/m^3

$\bar{\chi}_{max}$ -- time-averaged maximum ground level concentration, g/m^3

$\bar{\chi}_{max,i}$ -- time-averaged maximum ground level concentration of species i, g/m^3

$\bar{\chi}_{max,o}$ -- time-averaged maximum ground level concentration of reference species, g/m^3

SECTION 1

INTRODUCTION

The majority of homes within the United States are now heated by either natural gas (56%) or fuel oil (24%). These fuels have traditionally been inexpensive, easy to obtain, clean, and simple to burn in home furnaces. However, as natural gas and oil reserves diminish, it has become apparent that alternate energy sources must be developed for the residential sector. One candidate replacement fuel is coal.

Coal is the nation's most plentiful fuel, and in the past it was the predominant home heating fuel. At the present time, about 1% of the nation's homes are heated with coal. Recent advances in furnace design have made coal-fired residential furnaces easier to operate and nearly automatic. Consequently, the use of coal for home heating is attractive both economically and technically, and there are indications in some regions of the country of a trend toward increased home heating with coal.

One major drawback to residential coal combustion is increased air pollution. Both natural gas and fuel oil are cleaner fuels because they produce lower levels of pollutants than coal when burned in home heating devices. As a result, both regional and national EPA officials have become concerned over the potential environmental impact from increased residential coal combustion. A major changeover from natural gas or fuel oil to coal could produce a dramatic adverse effect on local air quality. For example, it is known that certain gases, trace elements, and organic compounds can have serious health effects in relatively low concentrations and that these materials are potential emissions from coal combustion sources.

This report presents a detailed characterization of emissions from residential coal combustion and an evaluation of their potential environmental effects. It describes the various types of combustion equipment, the present geographic distribution of coal-fired heating equipment, the different fuel types, and the combustion chemistry. Emission control technology and possible future trends of the source are also discussed.

Residential combustion of coal has been divided into the following categories:

- Residential combustion of anthracite coal
- Residential combustion of bituminous coal
- Residential combustion of lignite coal

These three source types are treated simultaneously in this report because of similarities in equipment, combustion conditions, and process emissions.

SECTION 2

SUMMARY

This report assesses the environmental impact of air emissions and solid residues produced by the residential combustion of coal, including anthracite, bituminous and lignite coal types. Estimated 1974 residential consumption of coal for primary heating was 2,610,000 metric tons;[a] 850,000 metric tons of anthracite, 1,740,000 metric tons of bituminous, and 20,000 metric tons of lignite. Coal was burned in approximately 490,000 heating devices located in all 50 states. Lignite is burned for residential purposes in North Dakota only; anthracite combustion is limited to northern states east of the Mississippi River with 64% in Pennsylvania; and bituminous coal is burned in every state except Connecticut, Delaware, Maine, Maryland, New Hampshire, New Jersey, North Dakota, Rhode Island, and Vermont. About 70% of all residential coal heating devices are located in the Appalachian coal region including the states of Alabama, Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. Pennsylvania alone has 28% of all coal-fired heating units and accounts for 30% of total residential coal consumption.

Coal-fired residential combustion sources are defined as those devices used to burn bituminous, anthracite and lignite coals to generate household heat. They are limited to units in occupied structures containing one or two housing units and generating up to 420 MJ/hr of heat. In 1970 about 55% of coal-fired residential primary heating devices were boilers and warm-air furnaces; the remaining units were heating stoves. Boilers and warm-air furnaces are usually stoker fed and are automatically controlled by a thermostat. They are generally designed to burn specific coal types. Other types of equipment used for residential coal combustion, especially for auxiliary heating, include room heaters, metal stoves, and metal and masonry fireplaces. These devices are generally less sophisticated and less energy efficient than boilers and furnaces.

The automatic stoker is the main component of automatic coal-fired heating units (i.e., boilers and warm-air furnaces). It consists of a hopper to store coal, a worm-fed mechanism to deliver coal for combustion, a retort where the coal burns, and a forced-draft fan that provides combustion air. The stoker is operated by a thermostat that activates the coal feed mechanism and combustion air fan when there is a demand for household heat. When the stoker is off, coal continues to burn slowly by natural draft combustion. A representative burning pattern for automatic combustion units is a total of 20 minutes of stoker operation and 40 minutes of natural draft combustion during each hour. The stoker design, method of operation, and use-burning cycle are significant parameters in determining the nature of emissions from automatic coal-fired heating devices. The design of the boiler or furnace used to recover heat is also important in the generation of emissions.

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[a] 1 metric ton = 10^6 grams; conversion factors and metric system prefixes are presented at the end of this report.

The composition and physical properties of coal, such as sulfur content, elemental content, volatile matter content, and free swelling index, are the other important factors in combustion-generated emissions. These properties can vary widely from one coal region to another. For example, coal trace element content ranges as much as two orders of magnitude for different bituminous coal types.

Residental combustion of coal produces emissions of particulates, sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrocarbons [including polycyclic organic materials (POM's)], carbon monoxide (CO), and trace elements. Uncontrolled mass emissions and emission factors are listed in Tables 1 and 2. Also presented are

TABLE 1. CRITERIA POLLUTANT EMISSIONS FROM COAL-FIRED RESIDENTIAL HEATING EQUIPMENT

Species	Emission factor,[a] g/kg[b]			Total annual emissions, metric tons/yr			Percent of national emissions, from all stationary sources		
	Bituminous	Anthracite	Lignite	Bituminous	Anthracite	Lignite	Bituminous	Anthracite	Lignite
Particulates	5.1	1.1	13.0	15,616	937	244	0.08	<0.01	<0.01
SO_x	15.0 S[c]	12.0 S[c]	15.0 S[c]	73,443[d]	6,916[d]	423[d]	0.2	0.02	<0.01
NO_x	3.9	0.9	3.0	6,035	769	56	0.02	<0.01	<0.01
Hydrocarbons	1.8	1.3	0.5	6,495	1,110	9	0.2	<0.01	<0.01
CO	13.0	8.3	1.0	65,104	7,088	19	0.05	0.01	<0.01

[a] Average for automatic units.

[b] Grams of pollutant per kilogram of fuel.

[c] S is sulfur content of coal expressed as percent.

[d] Based on average sulfur content of coals used by each state.

TABLE 2. NONCRITERIA POLLUTANT EMISSIONS FROM COAL-FIRED RESIDENTIAL COMBUSTION[a]

(g of pollutant/kg of fuel burned)

Species	Emission Factor		
	Bituminous	Anthracite	Lignite
Organic species:			
Polycyclic organic materials	0.058	0.001	
Polychlorinated biphenyls	<0.00005		
Formaldehyde	0.0012		
Elements:[b]			
Aluminum	1.6	2.0	3.7
Antimony	0.0008	0.0007	0.0002
Arsenic	0.02	0.005	0.005
Barium	0.01	0.01	0.04
Beryllium	0.0002	0.0002	0.00002
Bismuth	0.00001	0.00001	
Boron	0.003	0.0001	0.01
Bromine	0.01	0.001	
Cadmium	0.0005	0.0002	0.00008
Calcium	0.12	0.07	1.2
Chlorine	0.72	1.5	0.17
Chromium	0.002	0.002	0.0002
Cobalt	0.0007	0.0007	0.0001
Copper	0.002	0.003	0.0005
Fluorine	0.08	0.06	0.03
Gallium	0.005	0.005	0.0008
Iron	1.9	0.44	1.3
Lead	0.01	0.008	0.002
Lithium	0.003	0.003	0.0002
Magnesium	0.07	0.06	0.34
Manganese	0.06	0.002	0.005
Mercury	0.0002	0.0002	0.002
Molybdenum	0.002	0.002	0.002
Nickel	0.002	0.002	0.0002
Niobium	0.0005	0.0003	0.0002
Phosphorus	0.009	0.008	0.03
Potassium	0.23	0.24	0.02
Scandium	0.0005	0.0005	0.0001
Selenium	0.004	0.003	0.0006
Silicon	2.7	2.7	0.85
Silver	0.00002	0.002	0.001
Sodium	0.03	0.05	0.36
Strontium	0.01	0.01	0.03
Tellurium	0.0002	0.00005	
Thallium	0.00008	0.004	
Thorium	0.0005	0.0003	0.0004
Tin	0.0002	0.0001	0.00004
Titanium	0.09	0.15	0.03
Uranium	0.0001	0.0002	0.00007
Vanadium	0.002	0.002	0.0004
Ytterbium	0.001	0.001	0.00002
Yttrium	0.001	0.0001	0.0003
Zinc	0.02	0.012	0.002
Zirconium	0.005	0.005	0.001

[a] Blanks indicate data not available.

[b] Calculated values based on coal composition and limited test data.

the contributions of coal-fired residential combustion to national levels of criteria pollutant emissions (i.e., particulates, SO_x, NO_x, CO, and hydrocarbons). Sulfur oxide emissions from residential combustion of bituminous coal represent the greatest contribution to national criteria pollutant emissions from residential coal combustion. Residential combustion of lignite coal does not make a significant contribution to the national emission burden because this source is limited to North Dakota. Criteria pollutant emissions from residential bituminous combustion exceed 1% of the state totals in three states, while anthracite and lignite combustion criteria pollutant emissions are all less than 1% in every state, with most being less than 0.1%.

While the criteria pollutants emitted annually from residential coal combustion are a relatively small fraction of the total annual emissions of these pollutants, the emissions of POM's from this emission source may be significant. Annual emissions of POM's nationally in 1974 were about 101 metric tons from automatic bituminous-fired units and 0.9 metric tons from automatric anthracite-fired units, or about 10% of the total estimated national emissions of POM per year.

Combustion efficiencies for coal-fired residential heating equipment were lower than those for larger coal-fired systems (e.g., utility boilers) as evidenced by the high emission levels of CO, organic material, and POM compounds. Particulate emissions and POM emissions were affected by the type of combustion equipment, by coal properties such as coal volatile content and free swelling index, and by combustion equipment operating parameters. In contrast to the situation in utility boilers, coal ash did not have a significant effect on particulate emissions. Analysis of particulates showed that the composition is primarily carbon, indicating that particles were not formed from coal ash but from carbonaceous material volatilized during combustion.

One measure of the potential environmental effect of coal-fired residential combustion is the ratio of the time-averaged maximum ground level concentrations ($\bar{\chi}_{max}$) of species emitted from the source to an ambient air quality level or hazard factor (F). This ratio is called source severity (S), i.e., $S = \bar{\chi}_{max}/F$. For criteria emissions, F is the primary ambient air quality standard (AAQS), while for noncriteria emissions, F is a reduced threshold limit value (TLV®/300). Values for $\bar{\chi}_{max}$ are determined using a Gaussian plume dispersion model and average meteorological conditions.

An average combustion unit was determined for each coal type as a basis for severity calculations. All average coal-fired combustion devices were automatic units that discharge emissions to the atmosphere through an exhaust stack or chimney 6.1 m above ground level. An average bituminous coal-fired unit burns Appalachian coal at the rate of 1.1 kg/hr during the heating season or 5.4 metric tons per year, and it is located in an area with an average population density of 92 persons/km². The average anthracite coal-fired unit burns 6.1 metric tons of Pennsylvania anthracite coal per year at the rate of 1.2 kg/hr during the heating season and is located in an area with an average population density of 132 persons/km². Lignite-fired combustion units are located in North Dakota where the average population density is 4 persons/ km². The average unit burns 9.9 metric tons/yr of coal at 1.7 kg/hr during the heating season.

Table 3 gives the severities for the three average sources considered. Source severities were also determined for emissions from an array of 100 average houses burning coal. These severities, presented in Table 4, are approximately 30 times greater than the single source severities.

Another measure of potential environmental effect is the affected population, defined as the population around an average source that is exposed to a specified average ground level concentration of an emission species. These values are given for each source in Table 5 as those persons affected by emissions from a single source and from an array of 100 sources for $\bar{\chi}/F \geq 1.0$ and $\bar{\chi}/F \geq 0.05$. The only emission from a single source found to have an affected population where $\bar{\chi}/F \geq 1.0$ was POM. For an array of 100 homes, emissions of particulates, sulfur oxides, nitrogen oxides, hydrocarbons, and 16 individual elements had affected populations for $\bar{\chi}/F > 0.05$, but only POM had an affected population for $\bar{\chi}/F > 1.0$.

Emissions from residential combustion systems are not typically controlled with add-on equipment; however, proper design and operation of each unit can decrease emissions. Factors influencing emission levels include such items as fuel properties, fuel type, firing rate, firing equipment design, cyclic operation of automatic equipment, and excess air ratio.

Residential combustion of coal for primary heating has shown a steady decline since the 1940's. Even from 1970 to 1974, coal combustion for primary heating decreased about 60%. However, interest in this form of heating has revived since 1974. It is difficult to predict the impact the current shortage of oil and natural gas will have on the volume of coal combustion in the residential sector. Shipments of coal-fired heating equipment decreased until 1973, when the trend reversed. From 1962 to 1972, sales decreased by about 60%; but from 1972 to 1975 sales increased by 130% in the area of domestic heating stoves. Primary heating devices such as stoker furnaces began to shown an increase in sales in 1976.

TABLE 3. SOURCE SEVERITIES FOR COAL-FIRED RESIDENTIAL COMBUSTION EMISSIONS[a]

Emission species	Source severity[b]		
	Bituminous	Anthracite	Lignite
Particulates	3.0×10^{-3}	7.0×10^{-4}	1.0×10^{-2}
SO_x	2.0×10^{-2}	4.0×10^{-3}	1.0×10^{-2}
NO_x	9.0×10^{-3}	2.0×10^{-3}	1.0×10^{-2}
Hydrocarbons	2.0×10^{-3}	2.0×10^{-3}	1.0×10^{-3}
CO	7.0×10^{-5}	5.0×10^{-5}	1.0×10^{-5}
Polycyclic organic materials	2.6	5.0×10^{-2}	
Polychlorinated biphenyls	$<4.5 \times 10^{-7}$		
Formaldehyde	2.0×10^{-5}		
Elements:			
Aluminum	7.0×10^{-3}	1.0×10^{-2}	3.0×10^{-3}
Antimony	7.0×10^{-5}	7.0×10^{-5}	3.0×10^{-5}
Arsenic	2.0×10^{-3}	4.0×10^{-4}	7.0×10^{-4}
Barium	9.0×10^{-4}	1.0×10^{-3}	6.0×10^{-3}
Beryllium	5.0×10^{-3}	5.0×10^{-3}	7.0×10^{-4}
Bismuth	5.0×10^{-8}	5.0×10^{-8}	
Boron	1.0×10^{-5}	5.0×10^{-5}	8.0×10^{-5}
Bromine	7.0×10^{-4}	7.0×10^{-5}	
Cadmium	5.0×10^{-4}	7.0×10^{-4}	1.0×10^{-4}
Calcium	1.0×10^{-3}	1.3×10^{-2}	2.0×10^{-2}
Chlorine	5.0×10^{-3}	1.0×10^{-3}	2.0×10^{-3}
Chromium	9.0×10^{-4}	1.0×10^{-3}	1.0×10^{-4}
Cobalt	3.0×10^{-4}	3.0×10^{-4}	7.0×10^{-5}
Copper	1.0×10^{-4}	1.0×10^{-4}	3.0×10^{-5}
Fluorine	2.0×10^{-3}	2.0×10^{-3}	9.0×10^{-4}
Gallium	2.0×10^{-5}	3.0×10^{-5}	5.0×10^{-6}
Iron	2.0×10^{-2}	4.0×10^{-3}	2.0×10^{-2}
Lead	3.0×10^{-3}	2.0×10^{-3}	1.0×10^{-3}
Lithium	1.0×10^{-5}	2.0×10^{-5}	1.0×10^{-6}
Magnesium	3.0×10^{-4}	3.0×10^{-4}	2.0×10^{-3}
Manganese	6.0×10^{-4}	2.0×10^{-5}	7.0×10^{-5}
Mercury	2.0×10^{-4}	2.0×10^{-3}	1.0×10^{-4}
Molybdenum	2.0×10^{-5}	1.0×10^{-5}	2.0×10^{-5}
Nickel	7.0×10^{-4}	1.0×10^{-3}	1.0×10^{-4}
Niobium	2.0×10^{-6}	1.0×10^{-6}	1.0×10^{-6}
Phosphorus	4.0×10^{-4}	4.0×10^{-4}	2.0×10^{-3}
Potassium	5.0×10^{-3}	6.0×10^{-3}	7.0×10^{-4}
Scandium	2.0×10^{-6}	2.0×10^{-6}	7.0×10^{-7}
Selenium	8.0×10^{-4}	7.0×10^{-4}	2.0×10^{-4}
Silicon	1.0×10^{-2}	1.0×10^{-2}	6.0×10^{-3}
Silver	5.0×10^{-5}	5.0×10^{-3}	5.0×10^{-3}
Sodium	7.0×10^{-4}	1.0×10^{-3}	1.0×10^{-2}
Strontium	5.0×10^{-5}	5.0×10^{-5}	2.0×10^{-4}
Tellurium	5.0×10^{-5}	3.0×10^{-5}	
Thallium	3.0×10^{-5}	2.0×10^{-3}	
Thorium	2.0×10^{-6}	1.0×10^{-6}	3.0×10^{-6}
Tin	9.0×10^{-7}	5.0×10^{-7}	3.0×10^{-7}
Titanium	4.0×10^{-4}	7.0×10^{-4}	2.0×10^{-4}
Uranium	2.0×10^{-5}	5.0×10^{-5}	2.0×10^{-5}
Vanadium	2.0×10^{-4}	2.0×10^{-4}	6.0×10^{-5}
Ytterbium	5.0×10^{-7}	5.0×10^{-7}	1.0×10^{-7}
Yttrium	5.0×10^{-5}	5.0×10^{-5}	2.0×10^{-5}
Zinc	1.0×10^{-4}	1.0×10^{-4}	3.0×10^{-5}
Zirconium	5.0×10^{-5}	5.0×10^{-5}	1.0×10^{-5}

[a] Blanks indicate data not available.

[b] Based on fuel usage of a representative source.

TABLE 4. SOURCE SEVERITIES FOR COAL-FIRED RESIDENTIAL COMBUSTION EMISSIONS FROM MULTIPLE SOURCES[a]

Emission species	Source severity[b]		
	Bituminous	Anthracite	Lignite
Particulates	1.1×10^{-1}	2.0×10^{-2}	4.1×10^{-1}
SO_x	5.3×10^{-1}	1.3×10^{-1}	5.0×10^{-1}
NO_x	1.9×10^{-1}	5.0×10^{-2}	2.4×10^{-1}
Hydrocarbons	1.3×10^{-1}	5.0×10^{-2}	3.0×10^{-2}
CO	2.0×10^{-3}	1.0×10^{-3}	2.0×10^{-4}
Polycyclic organic materials	9.1×10^{1}	1.7	
Polychlorinated biphenyls	$<2.0 \times 10^{-5}$		
Formaldehyde	5.0×10^{-4}		
Elements:			
Aluminum	2.5×10^{-1}	3.4×10^{-1}	9.0×10^{-2}
Antimony	2.0×10^{-3}	2.0×10^{-3}	1.0×10^{-3}
Arsenic	6.0×10^{-2}	2.0×10^{-2}	3.0×10^{-2}
Barium	3.0×10^{-2}	3.0×10^{-2}	1.9×10^{-1}
Beryllium	1.6×10^{-1}	1.7×10^{-1}	2.0×10^{-2}
Bismuth	2.0×10^{-6}	2.0×10^{-6}	
Boron	5.0×10^{-4}	2.0×10^{-4}	3.0×10^{-3}
Bromine	2.0×10^{-3}	2.0×10^{-3}	
Cadmium	2.0×10^{-2}	8.0×10^{-3}	4.0×10^{-3}
Calcium	4.0×10^{-2}	2.0×10^{-2}	5.8×10^{-1}
Chlorine	1.6×10^{-1}	3.7×10^{-1}	6.0×10^{-2}
Chromium	3.0×10^{-2}	3.0×10^{-2}	5.0×10^{-3}
Cobalt	1.0×10^{-2}	1.0×10^{-2}	2.0×10^{-3}
Copper	4.0×10^{-3}	5.0×10^{-3}	1.0×10^{-3}
Fluorine	6.0×10^{-2}	5.0×10^{-2}	3.0×10^{-2}
Gallium	8.0×10^{-4}	9.0×10^{-4}	2.0×10^{-4}
Iron	6.0×10^{-1}	1.5×10^{-1}	6.3×10^{-1}
Lead	1.2×10^{-1}	9.0×10^{-2}	4.0×10^{-2}
Lithium	4.0×10^{-4}	6.0×10^{-4}	5.0×10^{-5}
Magnesium	1.0×10^{-3}	1.0×10^{-3}	8.0×10^{-3}
Manganese	2.0×10^{-2}	7.0×10^{-4}	2.0×10^{-3}
Mercury	6.0×10^{-3}	7.0×10^{-3}	5.0×10^{-3}
Molybdenum	7.0×10^{-4}	5.0×10^{-4}	7.0×10^{-4}
Nickel	2.0×10^{-2}	3.0×10^{-2}	5.0×10^{-3}
Niobium	2.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
Phosphorus	1.0×10^{-2}	1.0×10^{-2}	8.0×10^{-2}
Potassium	1.8×10^{-1}	2.1×10^{-1}	2.0×10^{-2}
Scandium	8.0×10^{-5}	9.0×10^{-5}	2.0×10^{-5}
Selenium	3.0×10^{-2}	3.0×10^{-2}	7.0×10^{-3}
Silicon	4.2×10^{-1}	4.6×10^{-1}	2.1×10^{-1}
Silver	3.0×10^{-3}	2.5×10^{-1}	2.5×10^{-1}
Sodium	3.0×10^{-2}	4.0×10^{-2}	4.4×10^{-1}
Strontium	2.0×10^{-3}	2.0×10^{-3}	8.0×10^{-3}
Tellurium	3.0×10^{-3}	1.0×10^{-3}	
Thallium	1.0×10^{-3}	6.0×10^{-2}	
Thorium	4.0×10^{-3}	3.0×10^{-3}	5.0×10^{-3}
Tin	3.0×10^{-5}	2.0×10^{-5}	1.0×10^{-5}
Titanium	1.0×10^{-2}	3.0×10^{-2}	8.0×10^{-3}
Uranium	8.0×10^{-4}	2.0×10^{-3}	9.0×10^{-4}
Vanadium	6.0×10^{-3}	7.0×10^{-3}	2.0×10^{-3}
Ytterbium	8.0×10^{-5}	2.0×10^{-5}	5.0×10^{-6}
Yttrium	2.0×10^{-3}	2.0×10^{-3}	7.0×10^{-4}
Zinc	5.0×10^{-3}	4.0×10^{-3}	1.0×10^{-3}
Zirconium	2.0×10^{-3}	2.0×10^{-3}	5.0×10^{-4}

[a] Blanks indicate data not available.

[b] Emissions assumed constant over a 24-hr period during the heating season.

TABLE 5. POPULATION EXPOSED TO EMISSIONS FROM AVERAGE COAL-FIRED RESIDENTIAL HEATING DEVICES
(Number of persons)

	Bituminous		Anthracite		Lignite	
Emission species[a]	$\bar{\chi}/F > 0.05$	$\bar{\chi}/F > 1.0$	$\bar{\chi}/F > 0.05$	$\bar{\chi}/F > 1.0$	$\bar{\chi}/F > 0.05$	$\bar{\chi}/F > 1.0$
Single source:						
POM	115	5	3	0	–[b]	–[b]
Multiple sources:						
Particulate	585	0	0	0	3,826	0
SO_x	4,361	0	783	0	>5,000[c]	0
NO_x	1,593	0	0	0	2,403	0
Hydrocarbons	783	0	0	0	0	0
POM	>5,000	>5,000	>5,000	352	0	0
Elements:						
Aluminum	2,537	0	3,326	0	394	0
Arsenic	98	0	0	0	0	0
Barium	0	0	0	0	1,560	0
Beryllium	1,174	0	1,218	0	0	0
Calcium	0	0	0	0	4,766	0
Chlorine	1,174	0	3,473	0	97	0
Fluorine	98	0	0	0	0	0
Iron	4,930	0	1,035	0	>5,000[c]	0
Lead	714	0	394	0	0	0
Magnesium	0	0	0	0	296	0
Phosphorus	0	0	0	0	296	0
Potassium	1,353	0	1,853	0	0	0
Silicon	3,826	0	3,852	0	1,853	0
Silver	0	0	2,537	0	2,537	0
Sodium	0	0	0	0	4,089	0
Thallium	0	0	98	0	0	0

[a] Only species with affected populations greater than zero are listed.

[b] Not determined.

[c] Actual number could not be determined.

U.S. Bureau of Census data up to 1975 indicate that residential heating with coal has continued to decline in all parts of the United States except the West, where 1975 usage showed a 50% increase over that in 1974. Recent reports from manufacturers and distributors of this equipment and from local and state officials show that there is a renewed interest in this type of heating. At this time, the magnitude of the trend cannot be predicted.

SECTION 3

SOURCE DESCRIPTION

Only 1% of U.S. housing units with primary heating devices burned coal for primary heating in 1974. Natural gas, the most popular heating fuel, was used in about 56% of the housing units (1). Emissions from the small fraction of housing units burning coal are major contributors to total national emissions from residential combustion. For example, in 1973, CO emissions from coal-fired residential combustion were estimated to be 79% of the total CO emitted from all residential sources (2).

Table 6 gives the breakdown of units heated by different fuel types (1).

TABLE 6. HOUSING UNITS HEATED BY A PARTICULAR FUEL

Fuel type	Housing units, 1974 (1)
Utility gas	39,471,000
Bottled, tank, or liquefied petroleum gas	4,143,000
Fuel oil, kerosene, etc.	16,835,000
Coal or coke	741,000
Wood	658,000
Electricity	8,407,000
Other fuels	90,000
Total	70,345,000

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(1) Current Housing Reports; Bureau of the Census Final Report H-150-74; Annual Housing Survey: 1974, Part A; General Housing Characteristics for the United States and Regions. U.S. Department of Commerce, Washington, D.C., August 1976. 179 pp.

(2) Surprenant, N., R. Hall, C. Young, D. Durocher, S. Slater, T. Susa, and M. Sussman. Volume II: Preliminary Emissions Assessment of Conventional Stationary Combustion Systems. EPA-600/2-76-046b, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1976. 523 pp.

SOURCE DEFINITION

Coal-fired residential combustion sources include all equipment that burns bituminous, anthracite, or lignite coal to generate household heat. These devices produce up to 420 MJ/hr of heat in occupied structures containing one or two housing units.

A negligible amount of coal is also used for cooking. Approximately 36,000 housing units were reported to use coal as cooking fuel in 1974 (1). These units amounted to only 5% of the housing units heating with coal. Considering that cooking utilizes about 10% of the energy needed for heating (3, 4), it follows that coal burned for cooking purposes is only about 0.5% of the coal burned in the residential sector for heating.

Also excluded from this source type are coal-fired devices located in large multiunit structures because they represent only a small portion of the total coal combustion for residential heating and are in the commercial/institutional size range. In 1970 approximately 80% of all housing units heated by coal were located in structures of less than three housing units (5).

EQUIPMENT DESCRIPTION

A wide variety of coal-fired heating equipment is available for residential usage. In 1970, coal-fired residential heating devices were distributed as follows: 16% steam or hot water boilers, 39% warm-air furnaces, and 45% domestic heating stoves (5). Figures 1, 2, and 3 show typical units on the market today (6-8).

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(3) Patterns of Energy Consumption in the United States. Prepared by Stanford Research Institute for Office of Science and Technology, Executive Office of the President, Washington, D.C., January 1972. 221 pp.

(4) Wells, R. M., and W. E. Corbett. Electrical Energy as an Alternate to Clean Fuels for Stationary Sources: Volume I. Contract 68-02-1319, Task 13, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1976. 181 pp.

(5) Census of Housing: 1970 Subject Reports; Bureau of the Census Final Report HC(7)-4; Structural Characteristics of the Housing Inventory. U.S. Department of Commerce, Washington, D.C., June 1973. 450 pp.

(6) Giammar, R. D., R. B. Engdahl, and R. E. Barrett. Emissions from Residential and Small Commercial Stoker- Coal-Fired Boilers Under Smokeless Operations. EPA-600/7-76-029, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, September 1976. 77 pp. (continued)

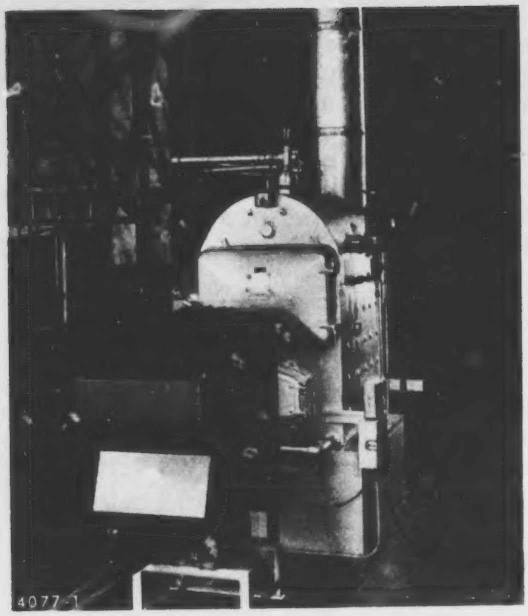


Figure 1. Stoker-fed residential coal-fired boiler (6).

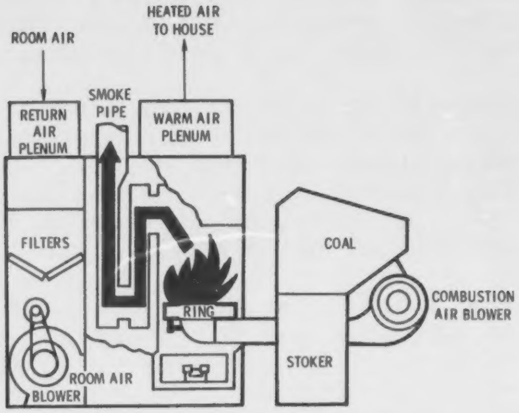
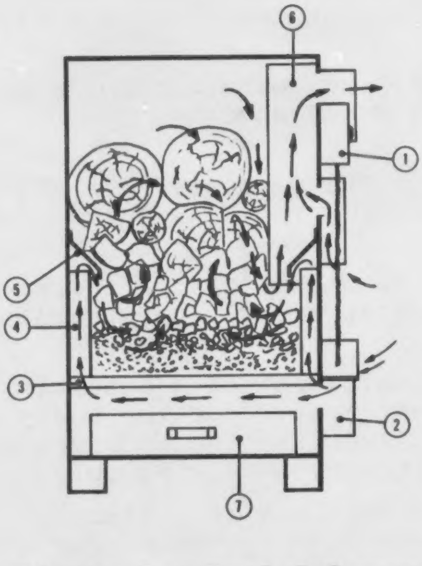

HEATED AIR TO HOUSE
ROOM AIR
SMOKE PIPE
RETURN AIR PLENUM
WARM AIR PLENUM
FILTERS
COAL
RING
COMBUSTION AIR BLOWER
STOKER
ROOM AIR
BLOWER

Figure 2. Cutaway view of stoker-fired residential furnace (7).



(1) THE REGULATOR - SETS THE DIAL FOR THE DESIRED TEMPERATURE. A BIMETAL COIL INSIDE THE REGULATOR RAISES A CHAIN CONNECTED TO THE MAGNETIC DAMPER (2).

(2) THE MAGNETIC DAMPER - AUTOMATICALLY ADMITS AIR WHEN THE REGULATOR CALLS FOR HEAT. AIR TRAVELS BELOW THE GRATE (3) AND BEHIND THE LINERS (4).

(3) GRATE - PROTECTED BY 50 - 75 mm LAYER OF ASH AT ALL TIMES.

(4) LINERS - AIR TRAVELS UPWARD BEHIND THE LINERS AN AND THEN IS DEFLECTED INTO THE COMBUSTION CHAMBER BY THE LINER RETAINERS.

(5) LINER RETAINERS

(6) GAS COMBUSTION FLUE - SMOKE IS FORCED DOWNWARD BACK INTO FIRE BEFORE IT CAN ENTER THE COMBUSTION FLUE. THE SECONDARY AIR PROVIDES THE OXYGEN NECESSARY FOR COMPLETE COMBUSTION TO OCCUR.

(7) ASH PAN

Figure 3. Hand-fed room heater for burning coal or wood (8).

Most boilers and warm-air furnaces are stoker-fed automatic heating devices controlled by thermostats. Thermostatically controlled stoves or room heaters are also on the market. Figure 4 is a schematic of an automatic coal-fired system. Typical automatic coal-fired systems consist of a fuel storage facility, fuel feed mechanism, combustion chamber and fan, heat transfer surface, heat delivery system, temperature controls, exhaust stack, ash chamber, and, in some cases, automatic ash removal system. Automatic residential coal-fired heating equipment ranges in size from about 76 MJ/hr to 420 MJ/hr (7, 9, 10, 11).

Because of uncertainties over fuel prices and fuel availability, some manufacturers are marketing units that have an interchangeable stoker and gas burner. Other furnaces contain both burner and stoker; the gas burner is ignited if the coal supply runs out. Although not stated in the manufacturers' literature, some coal-fired units can also be fired with wood chips (12).

Residential automatic coal-fired heating equipment is estimated to be about 55% to 60% efficient (3, 6, 13). This is difficult to verify, because the cyclic nature of the operation prevents an accurate determination of energy balances. Steady-state efficiencies are about 70% (14).

(continued)

(7) Prill's Self Cleaning Coal Furnaces (manufacturer's brochure). Prill Manufacturing Co., Sheridan, Wyoming. 2 pp.

(8) Riteway, the Quality Name in Energy Innovations (manufacturer's brochure). Riteway Manufacturing Co., Harrisonburg, Virginia. 12 pp.

(9) Weil-McLain 57 and 40 Coal-Fired Boilers (manufacturer's brochure). Weil-McLain Company, Inc., Michigan City, Indiana. 4 pp.

(10) Automatic Heat in a Single Package - The Combustioneer "77" Space Heater (manufacturer's brochure). The Will-Burt Company, Orrville, Ohio. 4 pp.

(11) Automatic Coal Heating with Hardin Automatic Coal Furnaces (manufacturer's brochure). S&S Manufacturing, Inc., Hardin, Montana. 2 pp.

(12) Heath, W. G. A Proposal for the Development of a Domestic Fuel Supply, Delivery, and Management System for the Rocky Boy's Indian Reservation, Montana. American Indian Development Association, Bellingham, Washington, 1976. 43 pp.

(13) Barrett, C. E., S. E. Miller, and D. W. Locklin. Field Investigation of Emissions from Combustion Equipment for Space Heating. EPA-R2-73-084a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1973. 213 pp.

(continued)

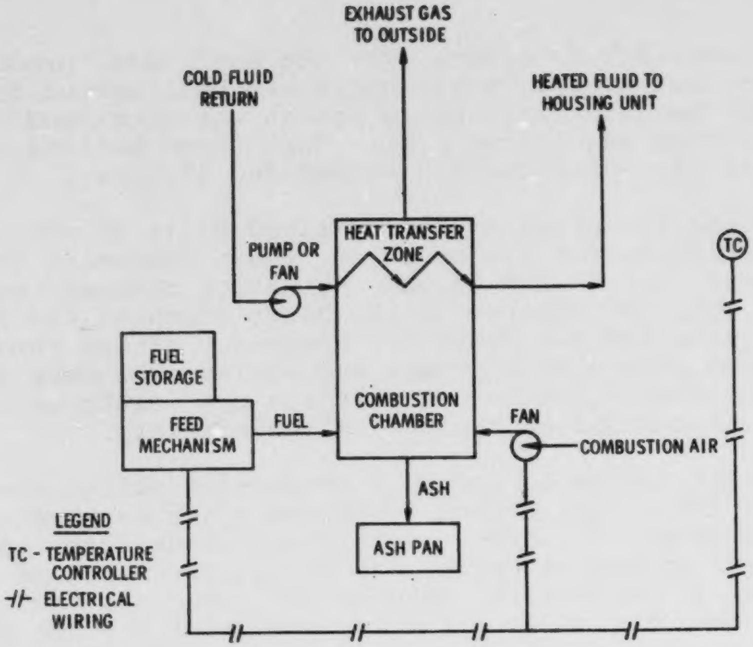

EXHAUST GAS TO OUTSIDE
COLD FLUID RETURN
HEATED FLUID TO HOUSING UNIT
HEAT TRANSFER ZONE
PUMP OR FAN
TC
FUEL STORAGE
FEED MECHANISM
FUEL
COMBUSTION CHAMBER
FAN
COMBUSTION AIR
ASH
ASH PAN
LEGEND
TC - TEMPERATURE CONTROLLER
-//- ELECTRICAL WIRING

Figure 4. Schematic of automatic coal-fired residential heating system for boiler or air furnace.

A problem with coal-fired residential combustion equipment is that only a limited range of different coal types can be efficiently burned in any particular unit. Coal-fired heating units are originally designed to burn a specific type of coal most efficiently, usually based upon the type of coal available in a certain region. Consequently, units designed to burn anthracite coal do not operate efficiently when fired with other coals such as bituminous. Even units designed to burn bituminous coal will not burn all bituminous coal effectively (6, 15, 16). The various types of combustion equipment and their operation are covered more specifically in the following sections.

(continued)

(14) Wells, R. M., and W. E. Corbett. Electrical Energy as an Alternate to Clean Fuels for Stationary Sources: Volume II Appendix. Contract 68-02-1319, Task 13, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1976. 527 pp.

(15) DeAngelis, D. G., and R. B. Reznik. Source Assessment: Coal-Fired Residential Combustion Equipment Field Tests, June 1977. EPA-600/2-78-004o, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1978. 94 pp.

(continued)

Boilers

Residential coal-fired boilers, for the most part, produce hot water rather than steam. These units are best suited for burning eastern coals because their basic design was developed when the only major market was in the East. Coal-fired boilers available today are usually automatic and stoker fed (Figure 1).

Typical designs for bituminous coal-fired units do not have separate facilities for ash removal. The arrangement is such that, as fresh fuel is fed to the combustion chamber, combustion residue, or ash, accumulates at the outer edges of the fuel bed and must be shoveled out by hand. Frequency of ash removal depends on the nature of the coal and may average once a day. Combustion of high volatile caking coals can result in large fused rings of combustion residue called clinkers.

Anthracite coal can be burned in a stoker-fed boiler when it is coupled with the proper stoker. Currently one manufacturer has a stoker available that effectively burns anthracite, and possibly other smokeless coals, and is equipped with an ash pit located below the combustion chamber (6). One manufacturer of automatic anthracite coal combustion equipment for residential heating has a unique design in which the fuel feed and combustion equipment are an integral part of the boiler. This unit employs the overfeed arrangement for feeding and burning coal (discussed later in Section 3 under "Combustion Process") but differs somewhat in combustion air flow. It is equipped with a cyclone for greater heat transfer and for fly ash removal from hot flue gases. Combustion is by induced draft rather than by forced draft as in conventional stoker systems (17).

Warm-Air Furnaces

Coal-fired residential warm-air furnaces have entered the market more recently than boilers and are increasing in popularity because of their modern design and adaptability to present household heat distribution systems (Figure 2). Present designs are limited to combustion of lignite and western subbituminous coal (18), although several manufacturers are exploring design modifications to burn a wider variety of coals.

(continued)

(16) A Survey of Coal-Fired Heating Equipment Manufacturers. Prepared by Mineral Economics Institute, Colorado School of Mines, for U.S. Department of the Interior, Bureau of Mines, March 4, 1977. 13 pp.

(17) The Completely New Way to Heat with Anthracite (manufacturer's brochure). Axeman-Anderson Company, Williamsport Pennsylvania. 6 pp.

Automatic coal-fired warm-air furnaces are fed by stokers similar in design to those used for coal-fired boilers. Several of these stokers have a rotating ring at the outer edges of the fuel bed to break up clinkers and force ash from the fuel bed area into a removable ash pan. These units are finding increasing demand in the West where most manufacturers are located.

Other Types of Coal-Fired Equipment

Besides the automatic coal-fired units just described, various other, less sophisticated devices can be used for residential combustion of coal. Such devices are used mostly for auxiliary heating but also for primary heating of small dwellings. Many of these units were originally designed to fire wood or wood and coal. These devices include room heaters (Figure 3), metal stoves, and metal and masonry fireplaces. Some devices can be thermostatically controlled, but most are hand fed and use combustion air induced by natural draft. Combustion efficiency is often controlled by a hand-operated damper in the exhaust stack or by adjustable openings in the doors of units that have them. Combustion efficiencies of these units vary widely and can be much lower than those for automatic units.

Automatic Stokers

A stoker is a mechanical device that feeds solid fuel to a combustion operation. Stokers employed for residential combustion are of the underfeed type; in addition to feeding the coal, they also provide supporting mechanisms for combustion such as the retort, wind box, and combustion air supply. Figure 5 (19) illustrates a typical stoker assembly.

During stoker operation a worm-feed mechanism conveys coal from a hopper to the fuel bed inside the furnace or boiler. A multiple grooved pulley on the motor controls the coal feed rate. Underfeed stokers deliver fresh coal to the fuel bed by feeding it underneath the hot coals. Below the fuel bed coal is devolatized and ignited in a cast iron chamber, or retort. The retort is surrounded by a wind box that delivers combustion air to the fuel bed through slotted holes called tuyeres. The tuyeres are part of a cast iron ring which in some units is rotated by the feed screw to break up clinkers and push ash to the outside of the fuel bed. Air for combustion is supplied by a blower located under the coal hopper and driven by the coal feed motor. Air flow can be controlled by a cover on the fan housing or by a

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(18) Personal communication with John O'Brien, Solid Fuel Systems, Inc., Englewood, Colorado, 17 December 1976.

(19) Domestic Stokers, Hopper and Bin Feed by Will-Burt (manufacturer's brochure). Form W346-75-2M, The Will-Burt Company, Orrville, Ohio. 4 pp.

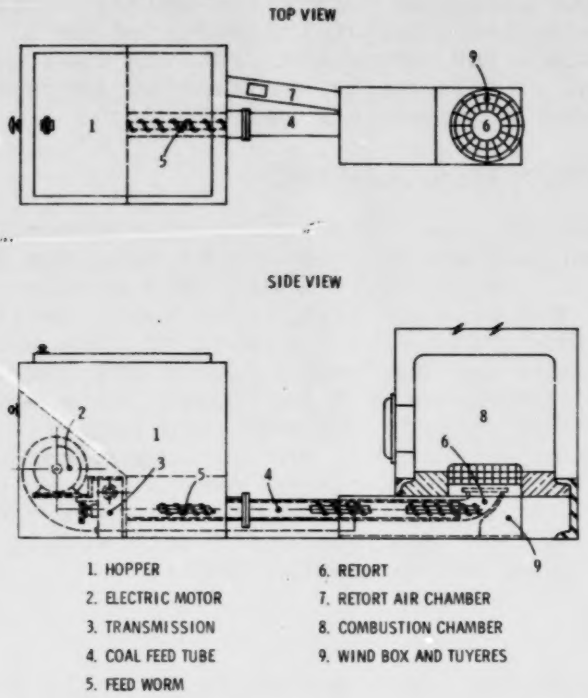
TOP VIEW
9
7
1
4
6
5
SIDE VIEW
2
1
3
5
4
8
6
9
1. HOPPER
2. ELECTRIC MOTOR
3. TRANSMISSION
4. COAL FEED TUBE
5. FEED WORM
6. RETORT
7. RETORT AIR CHAMBER
8. COMBUSTION CHAMBER
9. WIND BOX AND TUYERES

Figure 5. Will-Burt stoker assembly (19).

counterweight damper located in the air delivery tube. The motor driving the feed screw and the blower is controlled by a room thermostat, a limit switch, and a holdfire timing relay.

Operation of automatic stoker-fed coal-fired equipment eliminates the need for daily coal handling and manual adjustment of heat delivery. After a batch of coal is received from a dealer, the coal feed rate is adjusted to match the coal's heating value with the heating requirements. At the same time, the combustion air level is adjusted to provide adequate excess air to insure optimum combustion. The thermostat is then set to the desired temperature, and the only routine tasks left are charging the coal hopper and removing ash.

Stoker hoppers can hold up to a 2-week supply of coal, depending on the heating demand and fuel heating value. Bin-fed stokers are available as an alternative that eliminates the need to fill the hopper by hand. In this system, coal is fed directly from the storage bin to the burner. Depending on the type of coal burned and the heat demand, ashes need only be removed for disposal once every week to once every 4 weeks. In some cases ashes fall into a slide-out pan for easy removal.

Automatic Equipment Heating Cycle

Characteristic of automatic residential heating units is the thermostatically controlled heating cycle (ON/OFF cycle) sometimes referred to as the use-burning cycle. When the thermostat senses a drop in temperature, i.e., a demand for heat, the unit turns on and fuel is fed to the burner. When demand for heat is satisfied the unit turns off and the flow of fuel ceases.

Coal-fired residential heating units differ somewhat from gas- and oil-fired units in that air must be provided by a fan to maintain combustion in the fuel bed. Another difference is that residual coal continues to burn during the OFF segment even though no fuel is fed and the combustion fan is off. Combustion during the OFF segment of a heating cycle is at a much slower rate than during the ON segment because combustion is maintained only by natural draft from air leaks in the unit or draft vents in the combustion chamber door. The ON and OFF segments are sometimes referred to as high-fired and low-fire conditions, respectively.

The combustion cycle is a significant factor influencing emission rates from coal-fired residential combustion units. Emission data from similar units show significant differences in emission rates during the ON and OFF segments for the same emission species (6).

The ratio of heating unit ON/OFF time varies with the heating season. Thus the coldest months require a longer ON period while the warmer months require a longer OFF period. For coal-fired residential heating units this ratio is estimated to be 1:2 during the average portion of the heating season in moderate climates (see Appendix A). This corresponds to a total of 20 min of forced combustion out of every hour.

Two extremes occur during a heating season: full load and no load. During full load operation, the stoker runs continuously 25 minutes of every 30 minutes; a 5-minute "reset" period allows the fuel bed to cool and the ash to fuse. If the stoker is not stopped periodically, the ash will agglomerate, forming large clinkers which cause irregular burning. During no load operation, the stoker operates for about 5 minutes out of every 30 minutes to keep the fuel bed alive for quick response when the load increases.

Barometic Damper

Most automatic coal-fired combustion systems rely on a barometric damper to control draft through the fuel bed. Barometric dampers allow room air to enter the exhaust stack when the stack is placed under negative pressure due to atmospheric conditions. This is beneficial during the portion of a heating cycle when the stoker and fan are off and the fuel bed remains hot. An externally induced draft would cause more rapid combustion of residual coal during the OFF segment and could result in the fire burning out.

FUEL CHARACTERISTICS

Fuel types consumed by the residential combustion sources studied in this assessment are anthracite coal, bituminous coal, and lignite. The properties and composition of coal are important factors in its residential combustion. The following properties are important from an emission and operational standpoint.

Volatile Content

Coals with high volatile content have the potential for emitting high levels of particulates, hydrocarbons, and polycyclic organic materials (POM's), especially during the OFF segment of an automatic heating cycle (6, 15). Inefficient combustion of volatile matter is the cause for the associated high levels of emissions. A properly designed system may reduce emissions from the combustion of high volatile coals. Volatile matter in coal ranges from 14% to 47% for bituminous coal, 3% to 11% for anthracite coal, and 12% to 45% for lignite (20).

Free Swelling Index

The free swelling index of coal is a measure of its caking properties. Coals with a high free swelling index have a greater tendency to cake, or agglomerate, when burned. This can cause the fuel bed to degrade and form large fissures over a period of time, thus preventing the even distribution of air through the bed. Therefore, emissions associated with incomplete combustion are a potential problem when burning caking coals. Reducing the size of coal particles can reduce the caking properties of coals with high free-swelling index (6, 21). The free-swelling index for coals ranges from 0 to 9.0 for bituminous coal and is <1.0 for anthracite coal and lignite (21).

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(20) Swanson, V. E., J. H. Medlin, J. R. Hatch, S. L. Coleman, G. H. Wood, S. D. Woodruff, and R. T. Hildebrand. Collection, Chemical Analysis, and Evaluation of Coal Samples in 1975. Open-File Report 76-468, U.S. Department of the Interior, Denver, Colorado, 1976. 503 pp.

(21) Given, P. H. Some Comments on the Agglomerating Tendency of Coal. In: Proceedings of the Coal Agglomerization and Conversion Symposium (Morgantown, West Virginia, 5-6 May 1975), J. Smith, compiler. West Virginia University, Morgantown, West Virginia, April 1976.

Coal Size

Coal fines (less than 6.4 mm in diameter) are unavoidable due to crushing, screening, and feeding of coal. Excessive fines can interfere with uniform air distribution in the combustion process. They can also be entrained in combustion air and carried out in the flue gas (6). Historically, coal obtained for residential combustion has been of low quality from a size and contamination standpoint (22).

Ash Content

In residential combustion equipment, the amount of ash present is not as important as the ash properties. Coals with low ash-fusion temperatures may form clinkers that interfere with uniform feeding of coal and distribution of air. Ash content of coal typically ranges from 2% to 45% for bituminous coal, 5% to 45% for anthracite coal, and 3% to 41% for lignite (20) and is most significant in the amount of solid waste (combustion residue) generated.

Sulfur Content

The sulfur content of coal determines the level of SO_x emissions during combustion. However, in some western coals the high lime content in the ash reacts with some of the sulfur and reduces sulfur oxide emissions (6, 15, 23).

Nitrogen Content

Fuel nitrogen is known to contribute to NO_x emissions, but the level of conversion to NO_x is dependent on combustion conditions. High excess air increases NO_x formation, while lower temperatures decrease the amount formed (24).

Heat and Moisture Content

Both heating value and moisture content determine the coal feed rate. A coal such as lignite with low heating value requires a higher feed rate to meet the heating demand. So does a coal with a high moisture content, which acts as a diluent, reducing flame temperature and increasing sensible heat carried out by waste flue gases.

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(22) Personal communication with Stratton Schaeffer, Consulting Engineer, Camp Hill, Pennsylvania, 11 October 1977.

(23) Ctvrtnicek, T. E., S. J. Rusek, and C. W. Sandy. Evaluation of Low-Sulfur Western Coal: Characteristics, Utilization, and Combustion Experience. EPA-650/2-75-046, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, May 1975. 555 pp.

(24) Mitchell, R. E. Nitrogen Oxide Formation from Chemically-Bound Nitrogen During the Combustion of Fossil Fuels. SAND76-8227, Sandia Laboratories, Livermore, California, June 1976. 25 pp.

Heating values for coals range from 16 MJ/kg to 35 MJ/kg for bituminous and anthracite coals and 4.6 MJ/kg to 23 MJ/kg for lignite. Moisture contents range from 0.7% to 35% for bituminous coal, 0.5% to 4.0% for anthracite coal, and 23% to 53% for lignite (20).

Elemental Content

Coal has been shown to contain at least 74 elements in addition to carbon, hydrogen, and nitrogen (25). All of these elements are potential emissions when the coal is burned, either as part of the fly ash or in a volatilized form. Concentrations of these elements in coal can vary significantly from state to state, mine to mine, and even within the thickness of a coal seam. The concentration of a particular element in coal can range over two orders of magnitude (20, 25).

Tables 7 and 8 list average compositions and properties of U.S. coals burned in the residential sector (20, 21).

TABLE 7. AVERAGE COMPOSITION OF COAL, HEATING VALUE, AND FREE SWELLING INDEX (20, 21)

Property	All coal (488 samples)	Anthracite (38 samples)	Bituminous (277 samples)	Subbituminous (205 samples)	Lignite (28 samples)
Composition, percent:					
Moisture	10.0	1.4	4.8	18.4	41.5
Volatile matter	29.9	6.5	32.3	33.8	23.0
Fixed carbon	48.8	79.5	51.2	39.0	20.9
Ash	11.3	12.6	11.7	8.8	14.6
Hydrogen	5.1	2.4	5.0	5.9	6.8
Carbon	64.1	80.1	69.1	54.3	29.9
Nitrogen	1.1	0.8	1.3	1.0	0.5
Oxygen	16.4	3.2	10.3	29.3	46.5
Sulfur	2.0	0.8	2.7	0.7	1.7
Sulfate sulfur	0.12	0.02	0.16	0.04	0.24
Pyritic sulfur	1.19	0.35	1.70	0.35	0.68
Organic sulfur	0.70	0.48	0.88	0.32	0.75
Heating value:					
MJ/kg	26.0	29.7	28.5	21.9	11.6
(Btu/lb)	(11,180)	(12,780)	(12,260)	(9,410)	(5,000)
Free swelling index	0 to 9.0	0 to 0.5	3.0 to 9.0	0.5 to 3.0	0

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(25) Kessler, T., A. G. Sharkey, Jr., and R. A. Friedel. Analysis of Trace Elements in Coal by Spark-Source Mass Spectrometry. Report of Investigations 7714, U.S. Department of the Interior, Pittsburgh, Pennsylvania, 1973. 8 pp.

TABLE 8. AVERAGE CONCENTRATION OF 36 ELEMENTS IN COAL (20)[a]

Element	Units	All coal (799 samples)	Anthracite (53 samples)	Bituminous (509 samples)	Subbituminous (183 samples)	Lignite (54 samples)
Silicon	%	2.6	2.7	2.6	2.0	4.9
Aluminum	%	1.4	2.0	1.4	1.0	1.6
Calcium	%	0.54	0.07	0.33	0.78	1.2
Magnesium	%	0.12	0.06	0.08	0.18	0.31
Sodium	%	0.06	0.05	0.04	0.10	0.21
Potassium	%	0.18	0.24	0.21	0.06	0.20
Iron	%	1.6	0.44	2.2	0.52	2.0
Manganese	%	0.01	0.002	0.01	0.006	0.015
Titanium	%	0.08	0.15	0.08	0.05	0.12
Arsenic	ppm[b]	15	6	25	3	6
Cadmium	ppm	1.3	0.3	1.6	0.2	1.0
Copper	ppm	19	27	22	10	20
Fluorine	ppm	74	61	77	63	94
Mercury	ppm	0.18	0.15	0.20	0.12	0.16
Lithium	ppm	20	33	23	7	19
Lead	ppm	16	10	22	5	14
Antimony	ppm	1.1	0.9	1.4	0.7	0.7
Selenium	ppm	4.1	3.5	4.6	1.3	5.3
Thallium	ppm	4.7	5.4	5.0	3.3	6.3
Uranium	ppm	1.8	1.5	1.9	1.3	2.5
Zinc	ppm	39	16	53	19	30
Boron	ppm	50	10	50	70	100
Barium	ppm	150	100	100	300	300
Beryllium	ppm	2	1.5	2	0.7	2
Cobalt	ppm	7	7	7	2	5
Chromium	ppm	15	20	15	7	20
Gallium	ppm	7	7	7	3	7
Molybdenum	ppm	3	2	3	1.5	2
Niobium	ppm	3	3	3	5	5
Nickel	ppm	15	20	20	5	15
Scandium	ppm	3	5	3	2	5
Strontium	ppm	100	100	100	100	300
Vanadium	ppm	20	20	20	15	30
Yttrium	ppm	10	10	10	5	15
Ytterbium	ppm	1	1	1	0.5	1.5
Zirconium	ppm	30	50	30	20	50

[a] Whole-coal basis.

[b] Parts per million by weight.

AVERAGE SOURCE DEFINITION

To help evaluate the potential environmental effects of coal-fired residential combustion, it is useful to define typical or average combustion units. In this assessment, three separate average sources were defined; one each for residential heating units burning bituminous coal, anthracite coal, and lignite. Average sources are defined in terms of fuel characteristics, firing rate, emission height, and average population density around the source. The methodology employed to define the average source types is described in Appendix A.

Bituminous Coal-Fired Equipment

An average bituminous coal-fired residential combustion source is estimated to burn 1.1 kg/hr of coal during the heating season or 5.4 metric tons/yr in an automatically operated unit. It has a chimney discharging emissions to the atmosphere 6.1 m above ground level, and it is located in an area having an average population density of 92 persons/km^2.

The bituminous coal burned in the typical source originates in the Appalachian coal region. This is based on the fact that approximately 72% of all bituminous coal shipped to retailers in 1974 came from that region (26). The average analysis of Appalachian bituminous coal is presented in Table 9 (20, 27, 28).

Anthracite Coal-Fired Equipment

An average anthracite coal-firing residential combustion system is estimated to consume 1.2 kg/hr of coal during the heating season or 6.1 metric tons/yr. It has a chimney 6.1 m above ground level. The typical unit is located in an area with a population density of 132 persons/km^2. The anthracite coal burned in the representative source comes from eastern Pennsylvania and has an average analysis as shown in Table 10.

Lignite Coal-Fired Equipment

An average lignite coal-fired residential combustion source is located in North Dakota and is estimated to burn 1.7 kg/hr during the heating season or 9.9 metric tons/yr. It has a chimney height of 6.1 m and is located in an area having a population density of 4 persons/km^2. The coal burned in this source is North Dakota lignite and has the average analysis given in Table 11.

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(26) Mineral Industry Surveys, Bituminous Coal and Lignite Distribution, Calendar Year 1974. U.S. Department of the Interior, Washington, D.C., April 18, 1975. 74 pp.

(27) Ruch, R. R., H. J. Gluskoter, and N. F. Shimp. Occurrence and Distribution of Potentially Volatile Trace Elements in Coal. EPA-650/2-74-054, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July 1974. 96 pp.

(28) Magee, E. M., H. J. Hall, and G. M. Varga, Jr. Potential Pollutants in Fossil Fuels. EPA-R2-73-249 (PB 225 039), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1973. 223 pp.

TABLE 9. ARITHMETIC MEAN OF PROXIMATE AND ULTIMATE ANALYSES AND ELEMENTAL COMPOSITION FOR APPALACHIAN COAL REGION SAMPLES

Constituent	Arithmetic mean	Number of samples	Reference
Moisture, %	2.8	158	20
Volatile matter, %	31.6	158	20
Fixed carbon, %	54.6	158	20
Ash, %	11.0	158	20
Hydrogen, %	4.9	158	20
Carbon, %	72.6	158	20
Nitrogen, %	1.3	158	20
Oxygen, %	7.8	158	20
Sulfur, %	2.3	158	20
Heating value, MJ/kg	30	158	20
Elements, g/kg:			
Aluminum	16	331	20
Antimony	0.0012	331	20
Arsenic	0.027	331	20
Barium	0.100	331	20
Beryllium	0.002	331	20
Bismuth	0.0001	10	27
Boron	0.030	331	20
Bromine	0.011	19	20,27
Cadmium	0.0007	331	20
Calcium	1.2	331	20
Chlorine	0.72	19	20,27
Chromium	0.020	331	20
Cobalt	0.007	331	20
Copper	0.024	331	20
Fluorine	0.080	331	20
Gallium	0.007	331	20
Iron	19	331	20
Lead	0.0153	331	20
Lithium	0.0276	331	20
Magnesium	0.68	331	20
Manganese	0.62	331	20
Mercury	0.00024	331	20
Molybdenum	0.003	331	20
Nickel	0.015	331	20
Niobium	0.005	331	20
Phosphorus	0.09	14	20,27
Potassium	2.3	331	20
Scandium	0.005	331	20
Selenium	0.0047	331	20
Silicon	27	331	20
Silver	0.000[illegible]3	10	27
Sodium	0.32	331	20
Strontium	0.1	331	20
Tellurium	0.00034	10	27
Thallium	0.0001	10	27
Thorium	0.0048	331	20
Tin	0.0024	95	20,27,28
Titanium	0.9	331	20
Uranium	0.0014	331	20
Vanadium	0.020	331	20
Ytterbium	0.001	331	20
Yttrium	0.010	331	20
Zinc	0.020	331	20
Zirconium	0.050	331	20

TABLE 10. ARITHMETIC MEAN OF PROXIMATE AND ULTIMATE ANALYSES AND ELEMENTAL COMPOSITION FOR PENNSYLVANIA ANTHRACITE REGION SAMPLES

Constituent	Arithmetic mean	Number of samples	Reference
Moisture, %	1.4	38	20
Volatile matter, %	6.5	38	20
Fixed carbon, %	79.5	38	20
Ash, %	12.6	38	20
Hydrogen, %	2.4	38	20
Carbon, %	80.1	38	20
Nitrogen, %	0.8	38	20
Oxygen, %	3.2	38	20
Sulfur, %	0.8	38	20
Heating value, MJ/kg	29.7	38	20
Elements, g/kg:			
Aluminum	20	1	20
Antimony	0.0009	53	20
Arsenic	0.006	53	20
Barium	0.1	53	20
Beryllium	0.002	53	20
Bismuth	<0.0001	1	25
Boron	0.01	53	20
Bromine	0.001	1	25
Cadmium	0.0003	53	20
Calcium	0.7	53	20
Chlorine	1.5	1	25
Chromium	0.02	53	20
Cobalt	0.007	53	20
Copper	0.027	53	20
Fluorine	0.061	53	20
Gallium	0.007	53	20
Iron	4.4	53	20
Lead	0.01	53	20
Lithium	0.033	53	20
Magnesium	0.6	53	20
Manganese	0.02	53	20
Mercury	0.0002	53	20
Molybdenum	0.002	53	20
Nickel	0.02	53	20
Niobium	0.003	53	20
Phosphorus	0.075	1	25
Potassium	2.4	53	20
Scandium	0.005	53	20
Selenium	0.004	53	20
Silicon	27	53	20
Silver	0.003	1	25
Sodium	0.5	53	20
Strontium	0.1	53	20
Tellurium	<0.0001	1	25
Thallium	0.05	53	20
Thorium	0.003	1	25
Tin	0.001	1	25
Titanium	1.5	53	20
Uranium	0.002	53	20
Vanadium	0.02	53	20
Ytterbium	0.001	53	20
Yttrium	0.01	53	20
Zinc	0.016	53	20
Zirconium	0.05	53	20

TABLE 11. ARITHMETIC MEAN OF PROXIMATE AND ULTIMATE ANALYSES AND ELEMENTAL COMPOSITION FOR NORTH DAKOTA LIGNITE COAL SAMPLES

Constituent	Arithmetic mean	Number of samples	Reference
Moisture, %	29.7	7	20
Volatile matter, %	29.6	7	20
Fixed carbon, %	32.1	7	20
Ash, %	8.6	7	20
Hydrogen, %	6.1	7	20
Carbon, %	43.1	7	20
Nitrogen, %	0.7	7	20
Oxygen, %	40.0	7	20
Sulfur, %	1.5	7	20
Heating value, MJ/kg	16.7	7	20
Elements, g/kg:			
Aluminum	3.7	18	20
Antimony	0.0003	18	20
Arsenic	0.0067	18	20
Barium	0.4	18	20
Beryllium	0.0002	18	20
Boron	0.12	18	20
Cadmium	0.0001	18	20
Calcium	12	18	20
Chlorine	0.17	18	20
Chromium	0.002	18	20
Cobalt	0.001	18	20
Copper	0.0052	18	20
Fluorine	0.026	18	20
Gallium	0.0014	18	20
Iron	13	18	20
Lead	0.0034	18	20
Lithium	0.0021	18	20
Magnesium	3.43	18	20
Manganese	0.048	18	20
Nickel	0.002	18	20
Niobium	0.0022	18	20
Phosphorus	0.32	18	20
Potassium	0.2	18	20
Scandium	0.0012	16	20
Selenium	0.0008	18	20
Silicon	8.5	18	20
Silver	0.002	2	20
Sodium	3.57	18	20
Strontium	0.34	18	20
Thorium	0.0035	18	20
Tin	0.0004	5	28
Titanium	0.33	18	20
Uranium	0.0007	18	20
Vanadium	0.004	18	20
Ytterbium	0.0002	13	20
Yttrium	0.003	18	20
Zinc	0.0033	18	20
Zirconium	0.01	18	20

COMBUSTION PROCESS

General Description

Because of the varied nature of coal, a precise quantification of combustion chemistry is difficult to determine. The oxidation of hydrocarbons to carbon dioxide and water is only part of the reaction chemistry. Coals contain a variety of chemical constituents that may participate to some extent in reactions at high temperatures. Mineral substances such as silicates, sulfides, and halogen salts oxidize in the flame during combustion to form ash that is either retained in the fuel bed or entrained in the flue gas. Oxides of certain metals such as mercury and selenium have high vapor pressures and are thus partially volatilized during combustion. These vapors later condense in the postflame region and appear as ash, particulate emissions, or colloidal suspension in the flue gas.

The processes involved in the combustion of coal are illustrated in Figure 6 (29). Solid fuels burn in diffusion flames because the solid phase cannot be mixed with oxidants on a molecular scale. With the addition of radiant energy from an ignition device or the combustion zone, volatile components are vaporized and flow away from the solid surface while the solid portion of the fuel begins to pyrolyze. At this point, no oxidation of the fuel at the surface occurs due to lack of intimate contact with the oxidant. A diffusion flame is established where the mixing of combustibles and oxidant forms a combustible mixture. This is noted as the primary combustion zone. Additional transfer of heat results in additional vaporization of volatiles, pyrolysis, and a rise in surface temperature of the solid. After the depletion of volatiles, oxidation of the solid materials commences. Oxygen diffuses to the solid surface where oxidation of the nonvolatiles occurs, resulting in the release of more heat. Carbon monoxide and dioxide, water, hydrogen, nitrogen oxides, sulfur oxides, carbonaceous particulates from noncombusted vapors, and metallic oxides from noncombustible constituents may form or begin to form in the combustion zone.

The postflame region is that region directly downstream of the combustion zone. Many chemical and physical processes may occur in the postflame region because the reactants may be both gaseous and solid. Radical recombination reactions such as the recombination of atomic oxygen and the formation of water from atomic hydrogen and the hydroxyl radical occur as the combustion gases cool. Carbon dioxide and atomic hydrogen are formed by the combination of carbon monoxide and the hydroxyl radical. Pyrolytic

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(29) Edwards, J. B. Combustion, Formation, and Emission of Trace Species. Ann Arbor Science, Ann Arbor, Michigan, 1974. 240 pp.

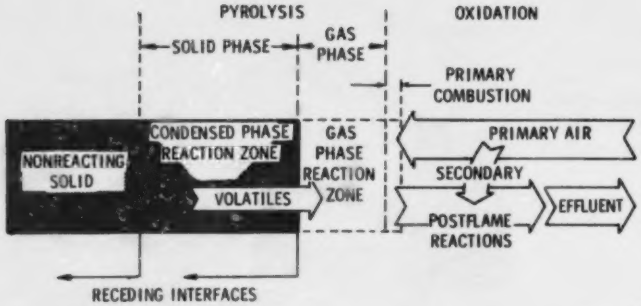
PYROLYSIS
OXIDATION
SOLID PHASE
GAS PHASE
PRIMARY COMBUSTION
CONDENSED PHASE REACTION ZONE
NONREACTING SOLID
VOLATILES
GAS PHASE REACTION ZONE
PRIMARY AIR
SECONDARY
POSTFLAME REACTIONS
EFFLUENT
RECEDING INTERFACES

Figure 6. Combustion of a solid (29).

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Combustion Formation and Emission of Trace Species, Copyright © 1974. Reprinted with permission of Ann Arbor Science Publishers, Inc.

reactions such as the reaction of fuel species and their products with other hydrocarbons, dehydrogenation of hydrocarbons to species of greater unsaturation, and the cracking of hydrocarbons are among the postflame reactions. Finally, nonash particulates may be formed by both condensation and agglomeration (29).

Combustion Geometry

Two basic fuel bed arrangements are used in residential coal-fired heating units, underfeed and overfeed. Each variation influences the combustion process and affects the emissions given off during combustion.

Underfeed Arrangement--

Automatic coal-fired residential combustion is usually carried out by underfeed stokers. Here the fuel is introduced at the bottom of the fuel bed flowing cocurrently with primary combustion air. Fresh fuel is not preheated by hot combustion gases, so evaporation of volatiles and oxidation of residual coal take place in the same region of the fuel bed.

With underfeeding, fresh coal introduced at the bottom of the bed forces ash to the top. It then spills over into an ash pit or is entrained in the flue gas. Secondary air above the fuel bed is not always provided in residential systems, resulting in high smoke levels when coals with a high volatile content are burned. Underfeed combustion is illustrated in Figure 7.

One characteristic of residential combustion of coal is the potential for caking and clinker formation. Clinkers form because the ash fuses at a low temperature; they can be harmful when they interfere with the uniformity of the fuel bed. Caking can occur when coals with a high free swelling index are burned. Combustion becomes unevenly distributed across the fuel bed, allowing unburned combustibles to leave the bed. Blow holes can

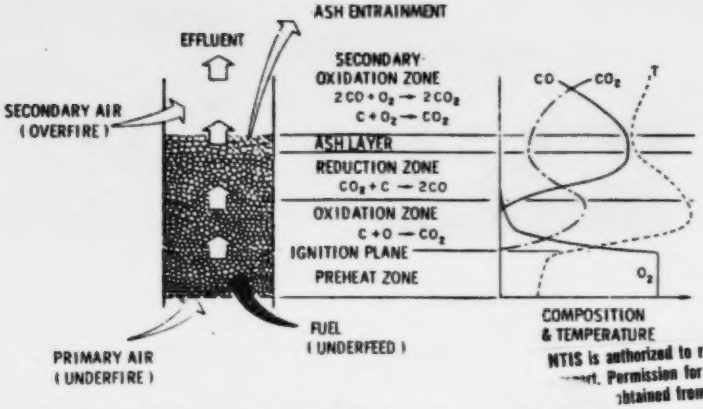
ASH ENTRAINMENT
EFFLUENT
SECONDARY OXIDATION ZONE
2CO + O₂ → 2CO₂
C + O₂ → CO₂
SECONDARY AIR (OVERFIRE)
ASH LAYER
REDUCTION ZONE
CO₂ + C → 2CO
OXIDATION ZONE
C + O → CO₂
IGNITION PLANE
PREHEAT ZONE
CO
CO₂
T
O₂
COMPOSITION & TEMPERATURE
FUEL (UNDERFEED)
PRIMARY AIR (UNDERFIRE)

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Figure 7. Underfeed arrangement of a solid fuel bed (29).

Combustion Formation and Emission of Trace Species, Copyright © 1974.
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also form in a caked bed; the resulting areas of high velocity gases entrain particulate matter.

Overfeed Arrangement--
Combustion of coal in fireplaces, stoves, or in any hand-fed system is represented by the overfeed arrangement of a fuel bed as illustrated in Figure 8. Some automatic combustion equipment also utilizes this arrangement.

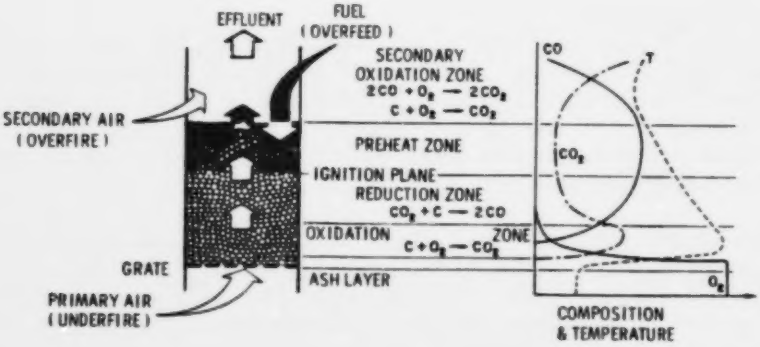
EFFLUENT
FUEL (OVERFEED)
SECONDARY OXIDATION ZONE
2CO + O₂ → 2CO₂
C + O₂ → CO₂
SECONDARY AIR (OVERFIRE)
PREHEAT ZONE
IGNITION PLANE
REDUCTION ZONE
CO₂ + C → 2CO
OXIDATION ZONE
C + O₂ → CO₂
GRATE
ASH LAYER
PRIMARY AIR (UNDERFIRE)
CO
CO₂
T
O₂
COMPOSITION & TEMPERATURE

Figure 8. Overfeed arrangement of a solid fuel bed (29).

Combustion Formation and Emission of Trace Species, Copyright © 1974.
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The air supply in the overfeed arrangement is divided between primary air fed under the bed (or grate) and secondary air introduced above the fuel bed. Primary air controls the rate of combustion because the coal cannot be consumed at a rate greater than the available oxygen permits. A deficiency or excess of primary air will reduce the bed temperature and the rate of combustion. Excess air levels as high as 7,000% have been measured for combustion of coal in fireplaces (30). Secondary air controls the overall combustion efficiency by oxidizing any unburned or partially oxidized combustible materials emitted from the fuel bed.

Overfeed firing has a major problem: as fresh fuel is supplied to the top of the bed, it is preheated with hot combustion gases, and its volatile components are driven off. Since little or no oxygen is present in this region, these volatile organics can only undergo pyrolytic reactions. Therefore, secondary air must be supplied for oxidation to take place above the fuel bed. However, excess secondary air can quench the reactions and produce partial oxidation products. Usually 30% to 50% total excess air is sufficient to compensate for incomplete mixing and allow complete combustion.

Hand-feeding of coal to a stable fuel bed results in the upset of a number of combustion process steps. At this stage of combustion, the flue gas contains the greatest load of combustible species, and the overall combustion process is least efficient (29).

GEOGRAPHICAL DISTRIBUTION

Coal-fired residential heating units are used throughout the United States and are concentrated near major coal regions. This distribution pattern reflects the desire of homeowners to burn fuel that is readily available and inexpensive.

The number of residential housing units heated with coal is compiled by the U.S. Bureau of Census, but the figure does not include homes using coal for auxiliary heat. In addition, some housing units are in multiunit structures having one common heat source. Thus the reported number of housing units heated by coal is not identical to the number of coal-fired heating devices. In this assessment, two reports from the 1970 Census of Housing (5, 31) were used in conjunction with the 1974 Annual Housing Survey (1) to estimate the actual population of coal-fired heating devices used in homes. (Details are presented in Appendix B.)

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(30) Snowden, W. D., D. A. Alguard, G. A. Swanson, and W. E. Stolberg. Source Sampling Residential Fireplaces for Emission Factor Development. EPA-450/3-76-010, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, November 1975. 173 pp.

(31) Census of Housing: 1970, Volume 1, Housing Characteristics for States, Cities, and Counties; Part 1: United States Summary. U.S. Department of Commerce, Washington, D.C., December 1972. 512 pp.

Coal consumption by the residential sector in 1974 was determined by using state fuel consumption data for 1972 (32, 33) in conjunction with information from the 1970 Census of Housing (5, 31). (Methodology is described in Appendix B.) The procedure for determining the 1972 fuel usage has been explained in the literature (32, 34, 35). There is no information available on the actual population of coal-fired combustion equipment used for auxiliary heating. It is estimated that the volume of coal burned for this purpose is insignificant when compared to the total coal consumed by the residential sector.

State-by-state data on coal heating equipment (i.e., number of units) and fuel usage appear in Tables 12 and 13, respectively. Kentucky and Tennessee account for 29% of the approximately 340,000 bituminous coal-fired devices. Alabama, Pennsylvania, Illinois, Ohio, North Carolina, Virginia, and West Virginia make up an additional 53% of the population. These nine states consume 83% of the bituminous coal burned in the residential sector.

There are approximately 160,000 anthracite-fired residential combustion units located in 16 states. Because anthracite coal is mined in Pennsylvania, these states are either located close to Pennsylvania or cannot readily obtain bituminous coal (e.g., the New England states). Pennsylvania contains 64% of the U.S. anthracite-fired residential furnaces while New York has 18%.

Residential combustion of lignite is assumed to be limited to the state of North Dakota. Most lignite is mined in Texas and North Dakota; however, Texas lignite is not sold to the residential sector on a commercial scale (36). Lignite is the only coal

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(32) 1973 NEDS Fuel Use Report. EPA 450/2-76-004 (PB 253 908), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, April 1976. 124 pp.

(33) Personal communication with C. Mann, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 11 November 1976.

(34) Guide for Compiling a Comprehensive Emission Inventory (Revised). Publication APTD-1135, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1973. 204 pp.

(35) Myers, J. P., and F. Benesh. Methodology for Countywide Estimation of Coal, Gas, and Organic Solvent Consumption. EPA-450/3-75-086, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, December 1975. 152 pp.

(36) Personal communication with D. Taylor, Texas Utility Generating Company, Dallas, Texas, 24 January 1977.

TABLE 12. ESTIMATED POPULATION OF COAL-FIRED PRIMARY RESIDENTIAL HEATING DEVICES, 1974

State	Number of primary residential heating devices[a]		
	Bituminous	Anthracite	Lignite
Alabama	19,754	0	0
Alaska	755	0	0
Arizona	89	0	0
Arkansas	941	0	0
California	277	0	0
Colorado	3,321	0	0
Connecticut	0	752	0
Delaware	0	625	0
Dist. Columbia	3,230	447	0
Florida	177	0	0
Georgia	9,121	0	0
Hawaii	33	0	0
Idaho	4,956	0	0
Illinois	27,995	557	0
Indiana	4,624	1,129	9
Iowa	1,377	0	0
Kansas	168	0	0
Kentucky	49,734	0	0
Louisiana	21	0	0
Maine	0	770	0
Maryland	0	7,879	0
Massachusetts	558	1,915	0
Michigan	4,625	1,587	0
Minnesota	1,727	0	0
Mississippi	1,940	0	0
Missouri	1,362	0	0
Montana	1,090	0	0
Nebraska	264	0	0
Nevada	170	0	0
New Hampshire	0	447	0
New Jersey	0	9,895	0
New Mexico	240	0	0
New York	346	27,513	0
North Carolina	17,644	0	0
North Dakota	0	0	996
Ohio	9,616	1,041	0
Oklahoma	159	0	0
Oregon	594	0	0
Pennsylvania	39,368	100,534	0
Rhode Island	0	132	0
South Carolina	8,568	0	0
South Dakota	299	0	0
Tennessee	46,404	0	0
Texas	130	0	0
Utah	4,326	0	0
Vermont	0	744	0
Virginia	34,156	0	0
Washington	2,899	0	0
West Virginia	29,001	0	0
Wisconsin	3,128	0	0
Wyoming	848	0	0
Total	336,035	155,987	996

[a] Located in structures of 1 or 2 housing units; derived from References 1 and 5 as in Appendix B.

TABLE 13. ESTIMATED DISTRIBUTION OF COAL USED FOR RESIDENTIAL COMBUSTION, 1974

State	Fuel usage,[a] metric tons/yr		
	Bituminous	Anthracite	Lignite
Alabama	61,264	0	0
Alaska	6,222	0	0
Arizona	363	0	0
Arkansas	4,461	0	0
California	1,667	0	0
Colorado	21,782	0	0
Connecticut	0	5,644	0
Delaware	0	3,690	0
Dist. Columbia	16,221	2,195	0
Florida	176	0	0
Georgia	8,118	0	0
Hawaii	15	0	0
Idaho	23,125	0	0
Illinois	216,670	4,462	0
Indiana	28,547	6,972	0
Iowa	10,322	0	0
Kansas	869	0	0
Kentucky	242,317	0	0
Louisiana	66	0	0
Maine	0	1,783	0
Maryland	0	48,285	0
Massachusetts	4,278	14,693	0
Michigan	22,448	7,701	0
Minnesota	26,050	0	0
Mississippi	5,453	0	0
Missouri	7,021	0	0
Montana	8,785	0	0
Nebraska	1,897	0	0
Nevada	1,112	0	0
New Hampshire	0	942	0
New Jersey	0	63,140	0
New Mexico	1,207	0	0
New York	1,663	132,246	0
North Carolina	69,434	0	0
North Dakota	0	0	18,784
Ohio	60,185	6,517	0
Oklahoma	758	0	0
Oregon	2,772	0	0
Pennsylvania	216,528	552,942	0
Rhode Island	0	932	0
South Carolina	25,932	0	0
South Dakota	4,405	0	0
Tennessee	220,007	0	0
Texas	365	0	0
Utah	29,427	0	0
Vermont	0	2,057	0
Virginia	166,946	0	0
Washington	10,945	0	0
West Virginia	185,318	0	0
Wisconsin	21,332	0	0
Wyoming	7,683	0	0
Total	1,744,156	854,201	18,784

[a] Primary heating fuel as derived in Appendix B from Reference 32 and Table 12.

mined in North Dakota and bituminous coal would not be competitive on a cost basis because of shipping charges (37). Therefore, the estimated 1,000 lignite-fired residential units located in North Dakota are assumed to be the only units firing lignite. Lignite is available in other states and may be burned there in the residential sector, but information was not available to permit quantification of these units.

A comparison of coal fields of the United States with the residential coal consumption by state (Figures 9 and 10) illustrates that consumption is greatest in or near major coal regions.

A comparison by consumption per capita and heating units per capita yields essentially the same results, with West Virginia having the greatest per capita coal consumption (100 metric tons/yr-1,000 people) and heating units (16 units/1,000 people).

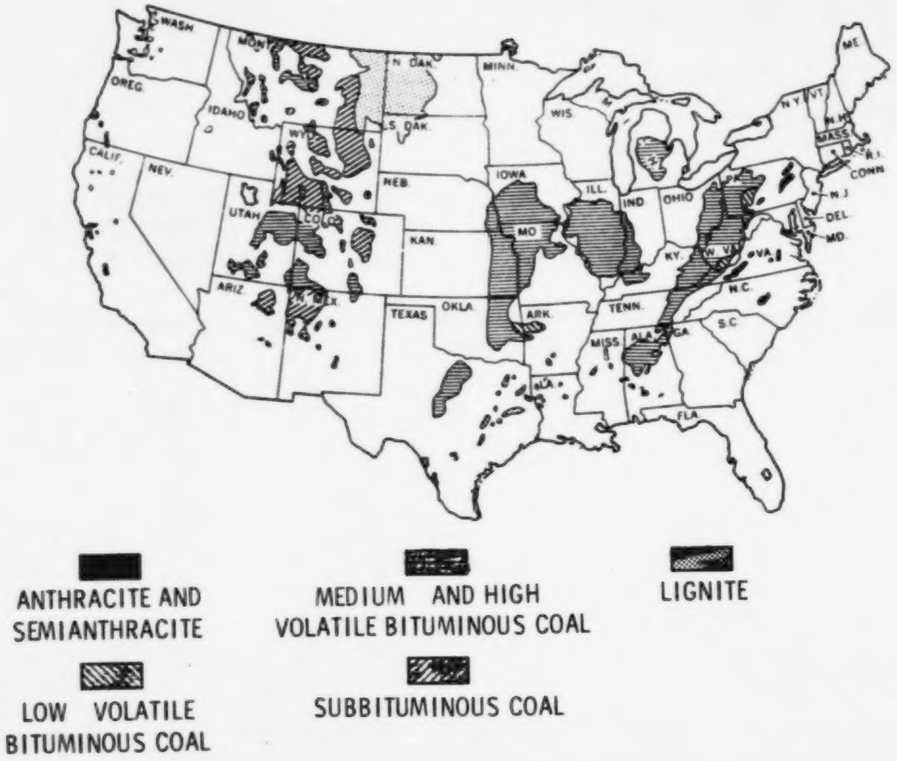
WASH
OREG.
CALIF.
NEV.
IDAHO
MONT.
WYO.
UTAH
COLO.
ARIZ.
N. MEX.
N. DAK.
S. DAK.
NEB.
KAN.
OKLA.
TEXAS
MINN.
IOWA
MO.
ARK.
LA.
WIS.
ILL.
IND.
OHIO
KY.
TENN.
MISS.
ALA.
GA.
FLA.
S.C.
N.C.
VA.
W. VA.
PA.
MD.
DEL.
N.J.
CONN.
R.I.
MASS.
N.Y.
VT.
N.H.
ME.
ANTHRACITE AND SEMIANTHRACITE
MEDIUM AND HIGH VOLATILE BITUMINOUS COAL
LIGNITE
LOW VOLATILE BITUMINOUS COAL
SUBBITUMINOUS COAL

Figure 9. Location of U.S. coal fields (28).

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(37) Personal communication with H. A. Cashion, North American Coal Corporation, Cleveland, Ohio, 24 January 1977.

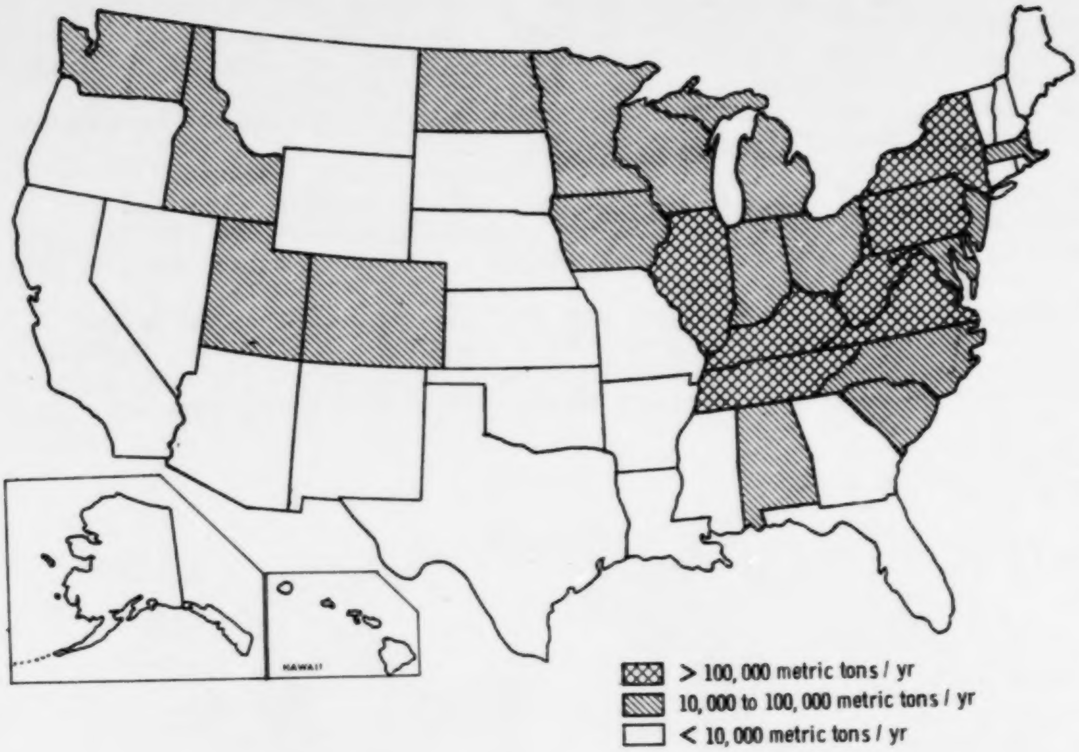
HAWAII
> 100, 000 metric tons / yr
10, 000 to 100, 000 metric tons / yr
< 10, 000 metric tons / yr

Figure 10. Estimated residential coal consumption in 1974 by state.

SECTION 4

EMISSIONS

Residential combustion of coal produces a number of atmospheric emissions and a solid residue. Atmospheric emissions include particulates, sulfur oxides, nitrogen oxides, carbon monoxide, hydrocarbons, POM's, and individual elements. Emissions are generated during the combustion process, and with the exception of a part of the nitrogen oxides, are formed from the coal as it burns. Some nitrogen oxide is formed by the combination of atmospheric nitrogen and oxygen at high temperatures in the furnace.

The solid residue is composed of inert material (ash) and unburned or partially burned fuel. If the solid residue is taken to a landfill for disposal, rainfall may leach out elements into water supplies.

Air emissions and solid residues are discussed separately in this section. A general discussion of emissions from three source types (anthracite, bituminous, and lignite) is followed by a detailed examination of individual emission species.

AIR EMISSIONS

Characterization of emissions from coal-fired residential combustion sources has concentrated on combustion of bituminous coal because of its widespread availability and use. Emissions from residential combustion of anthracite have been measured in only one test program, while lignite emission factors for residential combustion have been estimated based on tests on larger combustion systems. Average emission factors for each source type were developed by compilation of published emission data and emission estimates. Emissions data were also generated by a sampling program in which emissions from two bituminous coal-fired residential combustion units were quantified (15). Original data and procedures for emission factor development are presented in Appendix C. Average emission factors were determined for automatic coal-fired heating systems only. Data on hand-fed systems are limited and do not represent the current trend in coal heating.

The resulting average emission factors are presented in Table 14 (6, 15, 38-40). A comparison of the emission factors for criteria pollutants developed here with those published by the EPA (40) is given in Table 15.

Emission factors for SO_x and NO_x from residential combustion of bituminous coal compare well with those suggested by EPA (40). Emissions of hydrocarbons and CO are 2.5 to 3.5 times greater than those reported by the EPA, but this is understandable because the EPA values also represent larger units of greater combustion efficiency (40). The particulate emission factor differs from that reported by the EPA by a factor of two because the EPA value is based on coal ash content (40). It is shown later in this section that the ash content may not directly influence particulate emissions from residential combustion units. Average criteria pollutant emission factors for residential combustion of anthracite coal are generally less than the reported EPA values; however, a high degree of uncertainty is associated with the average emission factors developed in this study for anthracite combustion. A comparison for lignite combustion cannot be made because reliable emission data did not exist and Reference 40 was the only source of emission estimates for combustion units approaching the residential size range.

Emission data for all three source types were found in the published literature, but in several cases the adequacy of the data was questionable, and these values were not used in determining average emission factors. No data on the emission of individual elements could be found, and they were therefore measured through a special test program (15). The most reliable emissions data exist for criteria pollutants from residential combustion of bituminous coal. Several independent studies have been performed

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(38) Hangebrauck, R. P., D. J. Von Lehmden, and J. E. Meeker. Emissions of Polynuclear Hydrocarbons and Other Pollutants from Heat-Generation and Incineration Processes. Journal of the Air Pollution Control Association, 14(7):267-278, 1964.

(39) Hangebrauck, R. P., D. J. Von Lehmden, and J. E. Meeker. Sources of Polynuclear Hydrocarbons in the Atmosphere. Public Health Service Publication 999-AP-33 (PB 174 706), U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio, 1967. 44 pp.

(40) Compilation of Air Pollutant Emission Factors. Publication AP-42-A, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, February 1976. 216 pp.

TABLE 14. AVERAGE UNCONTROLLED EMISSION FACTORS FOR AUTOMATIC COAL-FIRED RESIDENTIAL COMBUSTION[a] (g of pollutant/kg of fuel)

	Bituminous		Anthracite		Lignite	
Emission species	Emission factor	Reference	Emission factor	Reference	Emission factor	Reference
Particulate	4.9	6, 15, 40	1.1	6	13.0	40
SO_x	15.0S[b]	6, 15, 38	12.0S[b]	6	15.0S[b]	40
NO_x	3.9	6, 15, 38	0.9	6	3.0	40
Hydrocarbons	1.8	15, 38, 39	1.3	40	0.5	40
CO	13.0	6, 15, 38	8.3	6	1.0	40
POM	0.058	6, 15, 38, 39	0.0001	6	1.0	40
Polychlorinated biphenyls	$<5 \times 10^{-6}$					
Formaldehyde	0.0012					
Elements:[c]						
Aluminum	1.6		2.0		0.37	
Antimony	0.0008		0.0007		0.0002	
Arsenic	0.02		0.005		0.005	
Barium	0.01		0.01		0.04	
Beryllium	0.0002		0.0002		0.00002	
Bismuth	0.00001		0.00001			
Boron	0.003		0.001		0.01	
Bromine	0.01		0.001			
Cadmium	0.0005		0.0002		0.00008	
Calcium	0.12		0.07		1.2	
Chlorine	0.72		1.5		0.17	
Chromium	0.002		0.002		0.0002	
Cobalt	0.0007		0.0007		0.0001	
Copper	0.002		0.003		0.0005	
Fluorine	0.08		0.06		0.03	
Gallium	0.005		0.005		0.0008	
Iron	1.9		0.44		1.3	
Lead	0.01		0.008		0.002	
Lithium	0.003		0.003		0.0002	
Magnesium	0.07		0.06		0.34	
Manganese	0.06		0.002		0.005	
Mercury	0.0002		0.0002		0.0001	
Molybdenum	0.002		0.002		0.002	
Nickel	0.002		0.002		0.0002	
Niobium	0.0005		0.0003		0.0002	
Phosphorus	0.009		0.008		0.03	
Potassium	0.23		0.24		0.02	
Scandium	0.0005		0.0005		0.0001	
Selenium	0.004		0.003		0.0006	
Silicon	2.7		2.7		0.85	
Silver	0.00002		0.002		0.001	
Sodium	0.03		0.05		0.36	
Strontium	0.01		0.01		0.03	
Tellurium	0.0002		0.0005			
Thallium	0.00008		0.004			
Tharium	0.0005		0.0003		0.0004	
Tin	0.0002		0.0001		0.00004	
Titanium	0.09		0.15		0.03	
Uranium	0.0001		0.0002		0.00007	
Vanadium	0.002		0.002		0.0004	
Ytterbium	0.0001		0.0001		0.00002	
Yttrium	0.001		0.001		0.0003	
Zinc	0.02		0.012		0.002	
Zirconium	0.005		0.005		0.001	

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[a] Blanks indicate no data available.

[b] S is the coal sulfur content in percent.

[c] Emission factors based on the individual element's average coal concentration and partitioning behavior.

TABLE 15. EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL COMBUSTION AS COMPARED TO THOSE IN AP-42 (40)

Emission species	Emission factors, g of pollutant/kg of fuel					
	Bituminous		Anthracite		Lignite	
	This study	AP-42[a]	This study	AP-42[b]	This study	AP-42[c]
Particulate	4.9	11.0[d]	1.1	5.0	e	13.0[f]
SO_x	15.0S[g]	19.0S[g]	12.0S[g]	18.4S[g]	e	15.0S[g]
NO_x	3.9	3.0	0.9	1.5	e	3.0
Hydrocarbons	3.9	1.5	1.3	1.25	e	0.5
CO	17.0	5.0	8.3	45.0	e	1.0

[a] Spreader stoker units <11 GJ/hr.

[b] Hand-fed units.

[c] Stoker-fed other than spreader stoker.

[d] Based on average ash content of 11.0% (Appalachian coal) (20).

[e] No data available; used AP-42 (40).

[f] Based on average ash level of 8.6% (20).

[g] S is the coal sulfur content in percent.

over the past 14 years employing various types of combustion equipment, grades of bituminous coal, and operating conditions that together cover the range of conditions expected during actual operation. Emission factors from combustion of bituminous coal in each test program are presented in Table 16 by type of combustion equipment and grade of bituminous coal, when available. Other pertinent parameters, such as percent excess air and equipment size, are also given. Emission tests of hand-fed units are included in Table 16 for comparison. The only data rejected from this study were recent measurements of SO_x, particulate, and CO emissions from a bituminous coal-fired warm-air furnace (41). The results from that study are not included because of discrepancies found in emission data (i.e., measured SO_x emissions accounted for <2% of the coal sulfur).

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(41) Briggs, D. Testing of Particulate and Sulfur Oxide Emissions from a Residential Furnace. Laboratory Number 10638, Coors/Spectro-Chemical Laboratory, Golden, Colorado, January 22, 1976. 19 pp.

TABLE 16. EMISSION FACTORS FOR RESIDENTIAL SIZE BITUMINOUS COAL COMBUSTION UNITS FROM INDIVIDUAL TEST PROGRAMS (g of pollutant/kg of fuel)

	Monsanto Research Corporation (15)										
	Stoker-fed boiler						Stoker-fed furnace				
	High volatile B bituminous coal			High volatile C bituminous coal			High volatile C bituminous coal			Western sub-bituminous coal	
	Emission factor		Number of tests	Emission factor		Number of tests	Emission factor		Number of tests	Emission factor	Number of tests
Emission species	Average	Range		Average	Range		Average	Range			
Particulates	3.3[a]	1.5 - 4.1	6	2.2[a]	1.1 - 3.1	6	15[a]	9.7 - 25	8	2.0[a]	1
Sulfur oxides[b]	10S[c]	7.1S - 15S	4	12S[c]	5.95S - 18S	5	11S[c]	7.6S - 15S	6	-[d]	-[d]
Nitrogen oxides	4.5[e]	2.7 - 6.4	6	2.3[e]	1.0 - 4.0	6	5.1[e]	2.7 - 11	8	-[d]	-[d]
Hydrocarbons	1.1[f]	0.93 - 1.4	4	1.8[f]	1.1 - 29	6	3.6[f]	2.2 - 6.0	4	1.8[f]	1
Carbon monoxide	0.8	0.08 - 2.9	6	<2.5	<0.04 - 15	6	11	4.4 - 17	6	-[d]	-[d]
POM	0.21	0.13 - 0.29	2	-[d]	-[d]	-[d]	0.024	0.017 - 0.035	3	-[d]	-[d]
Polychlorinated biphenyl	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	$<5 \times 10^{-\text{[illegible]}}$[g]	-[d]	1	-[d]	-[d]
Formaldehyde	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]
	Test conditions										
Equipment output capacity, MJ/hr	211			211			211			211	
Operating cycle, min ON/min OFF	20/40			20/40			20/40			20/40	
Coal feed rate, kg/hr	9.7 - 10			7.0 - 9.6			6.8 - 7.2			10	
Excess combustion air, %	120 - 238			109 - 221			92 - 202			207	
Coal ash content, %	4.3 - 10.9			5.0 - 9.1			5.0 - 9.1			3.3	
Coal volatile content, %	39.1 - 42.3			37.5 - 38.8			37.5 - 38.8			34.7	
Coal sulfur content, %	0.4			0.6 - 1.5			0.6 - 1.5			0.5	
Coal heating value, MJ/kg	26.7 - 28.7			24.6 - 26.9			24.6 - 26.9			22.4	
Free-swelling index	1			0 - 0.5			0 - 0.5			0	

(continued)

TABLE 16 (continued)

Emission species	Battelle-Columbus Laboratories[h] (16)							
	Stoker-fed boiler							
	High volatile bituminous coal			Western subbituminous coal			Low volatile bituminous coal	
	Emission factor		Number of tests	Emission factor		Number of tests	Emission factor	Number of tests
	Average	Range		Average	Range			
Particulates	7.4[a]	4.6 - 9.0	4	1.6[a]	0.95 - 2.2	5	3.1[a]	1
Sulfur oxides[b]	24S[c]	23S - 2.65	2	18S[c]	13S - 23S	2	-[d]	-[d]
Nitrogen oxides	3.2[i]	3.0 - 3.3	3	2.6[i]	2.1 - 3.0	3	4.6[i]	1
Hydrocarbons	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]
Carbon monoxide	32	9 - 69	3	15	9.3 - 18	4	10	1
POM	0.1	0.012 - 0.19	4	0.016	0.008 - 0.022	4	0.06	1
Polychlorinated biphenyl	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]
Formaldehyde	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]	-[d]
	Test conditions							
Equipment output capacity, MJ/hr		720			720		720	
Operating cycle, min ON/min OFF		20/40			20/40		20/40	
Coal feed rate, kg/hr		10 - 34			11 - 34		23	
Excess combustion air, %		30 - 116			40 - 190		132	
Coal ash content, %		4.7			9.2		6.9	
Coal volatile content, %		40			37.4		21.4	
Coal sulfur content, %		1.2			0.6		0.6	
Coal heating valve, MJ/kg		32.8			26.5		34.1	
Free-swelling index		5			0.5		7.5	

(continued)

TABLE 16 (continued)

Emission species	Hangebrauck - 1967 (39)								
	Stoker-fed boiler			Stoker-fed furnace			Hand-fed furnace		
	Bituminous coal			Bituminous coal			Bituminous coal		
	Emission factor		Number of tests	Emission factor		Number of tests	Emission Factor		Number of tests
	Average	Range		Average	Range		Average	Range	
Particulates	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}
Sulfur oxides[b]	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}
Nitrogen oxides	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}
Hydrocarbons	1.9[j]	1.4 - 2.4	2	0.46[j]	0.3 - 0.6	2	8.2[j]	5.3 - 11	2
Carbon monoxide	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}
POM	0.038	0.031 - 0.045	2	0.016	0.006 - 0.026	2	0.83	0.46 - 1.2	2
Polychlorinated biphenyl	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}
Formaldehyde	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}	-^{d}
	Test conditions								
Equipment output capacity, MJ/hr		-^{d}			-^{d}			-^{d}	
Operating cycle, min ON/min OFF		60/0			60/0			60/0	
Coal feed rate, kg/hr		1.7 - 1.9			2.0 - 2.3			2.5 - 2.9	
Excess combustion air, %		-^{d}			-^{d}			-^{d}	
Coal ash content, %		4.0			2.4			2.9	
Coal volatile content, %		-^{d}			-^{d}			-^{d}	
Coal sulfur content, %		33.2			32.5			33.0	
Coal heating valve, MJ/kg		-^{d}			-^{d}			-^{d}	
Free-swelling index		-^{d}			-^{d}			-^{d}	

(continued)

TABLE 16 (continued)

Emission species	Hangebrauck - 1964 (38) Stoker-fed boiler Bituminous coal Emission factor	Number of tests	Hangebrauck - 1964 (38) Hand-fed furnace Bituminous coal Emission factor	Number of tests	Snowden (30) Fireplace Bituminous coal Emission factor	Number of tests
Particulates	6[k]	1	19[k]	1	7.0[a]	1
Sulfur oxides[b]	165S[c]	1	165S[c]	1	–[d]	–[d]
Nitrogen oxides	4.9[e]	1	1.6[e]	1	–[d]	–[d]
Hydrocarbons	1.7[ℓ]	1	11[ℓ]	1	7.4[f]	1
Carbon monoxide	16	1	50	1	–[d]	–[d]
POM	0.003	1	0.13	1	–[d]	–[d]
Polychlorinated biphenyl	–[d]	–[d]	–[d]	–[d]	–[d]	–[d]
Formaldehyde	–[d]	–[d]	0.0012	1	–[d]	–[d]
			Test conditions			
Equipment output capacity, MJ/hr	169		211		–[d]	
Operating cycle, min ON/min OFF	60/0		60/0		–[d]	
Coal feed rate, kg/hr	2.2		3.6		0.5	
Excess combustion air, %	417		538		–[d]	
Coal ash content, %	3.9		2.7		–[d]	
Coal volatile content, %	1.0		0.5		–[d]	
Coal sulfur content, %	31.9		33.4		–[d]	
Coal heating valve, MJ/kg	38		38		–[d]	
Free-swelling index	–[d]		–[d]		–[d]	

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[a] Front half of EPA Method 5 only.

[b] Reported as SO_2.

[c] S is sulfur content of fuel in weight percent.

[d] No measurement made or reported.

[e] Reported as NO_2.

[f] Determined condensed organic material residue weight in the EPA Method 5 impinger train.

[g] Detection limit.

[h] Barometric damper sealed shut.

[i] Reported as NO.

[j] Benzene soluble fraction of organic material trapped in a 32°F and -98°F bubbler system.

[k] Includes front and back half material from EPA Method 5 characterization.

[ℓ] Reported as methane determined by flame ionization.

Emission data for residential combustion of anthracite coal were obtained from one study in which two tests were conducted. Because of the limited emission data, the average emission factors are highly uncertain. However, based on comparison with bituminous coal-fired emissions, it is anticipated that the actual average emission factors for anthracite combustion do not exceed the uncertainty limits given in Table 14.

Criteria pollutant emission factors presented for residential combustion of lignite are estimates suggested by the EPA because emission data could not be obtained for this source type. Particulates and SO_x were measured in one recent test on a 106 MJ/hr furnace burning lignite (42), but the particulate emission factor of 1.0 g/kg could not be supported by other data and is an order of magnitude below that suggested by the EPA based on coal ash content. The SO_x emission factor of 15S[a] g/kg is reasonable, based on studies of other coal types, and closely agrees with EPA estimates. An additional study measured particulate emissions on a commercial/institutional size lignite-fired boiler and found an average particulate emission factor of 13 g/kg (43). Although much larger than residential units, this boiler is still relatively small and its emission may approximate those from residential units. The order of magnitude discrepancy between the particulate emission factors for the two studies indicates that there are insufficient data to substantiate whether either study is representative of residential emissions.

Emissions of individual elements from coal-fired residential combustion units had not been measured prior to this study. A special project (15) related to this investigation included measurement of emissions of individual elements from two coal-fired units burning a limited range of bituminous coals. Because coal elemental content can vary by several orders of magnitude, these data are too limited to represent average elemental emission factors for residential combustion of bituminous coal. However, the elemental emission data were used in conjunction with the associated coal analysis to estimate the upper limits of coal elements emitted to the atmosphere. A more detailed explanation is presented later in this section.

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[a] S is coal sulfur content.

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(42) Sulfur in Colorado Lignite. Cameron Engineering, Inc., Denver, Colorado, June, 1977.

(43) Results of the August 16, 1977 Particulate emission Compliance Test of the Beulah High School No. 3 Boiler, Beulah, North Dakota. Report Number 7-334, Interpoll, Inc., St. Paul, Minnesota, August 31, 1977. 24 pp.

Emission factors for coal-fired residential combustion are influenced by many variables, but in general the data suggest that burning anthracite or western subbituminous coal in a stoker-fed unit has the least environmental impact. Choosing the proper equipment design and burning the coal most suited for the equipment are other important considerations. Emission rates for species are directly or indirectly affected by specific parameters of coal type and equipment design and operation. These parameters interact in a complex manner and make prediction of emission factors based on parameters a difficult task. The following discussion of each emission species reports what is presently known about those factors that affect emission rates. It is based, for the most part, on observations from testing programs burning bituminous coals.

Particulates

Particulate emissions consist of small, discrete masses of solid or liquid leaving the exhaust stack of residential combustion equipment. The most frequently employed method for collection and quantification of these emissions is the EPA Method 5 (44). This system collects particulates in two fractions, segregating solid particles (front half) from condensed vapors (back half). Most studies have reported material collected in the front half as particulate emissions. This report remains consistent with that practice and classifies the material collected in the back half as organic emissions. Reference 38 reported the total material collected as particulate emissions and therefore was excluded in the calculation of the average particulate emission factor.

Estimates of particulate emission factors for coal-fired residential combustion are in terms of the coal ash content; however, it has been demonstrated that ash content may not directly affect particulate emissions (15). Analysis of particulates for carbon, hydrogen, and nitrogen before and after extraction with methylene chloride (CH_2Cl_2) (Table 17) demonstrates that particulate emissions contain unextractable carbon in approximately the same concentration as that in the feed coal (15).

The carbonaceous nature of the particulate emissions explains the lack of correlation between particulate emission factors and coal ash content. In large coal-fired combustion units (e.g., utility boilers), particulate emissions arise from inorganic matter (ash) contained in the coal. However, in residential units the combustion process is less efficient, and particles are apparently formed by volatilization and subsequent condensation of carbonaceous matter in the coal. This hypothesis is supported by the

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(44) Standards of Performance for New Stationary Sources. Federal Register, 42(160):41776-41782, 1977.

TABLE 17. AVERAGE CARBON, HYDROGEN, AND NITROGEN CONTENT OF PARTICULATE EMISSIONS FROM COAL-FIRED RESIDENTIAL HEATING SYSTEMS (15)

Sample identification	Composition, percent of particulate		
	Carbon	Hydrogen	Nitrogen
Particulate train filter catch before extraction with CH_2Cl_2	80.1	1.4	0.7
Particulate train filter catch after extraction with CH_2Cl_2	79.8	1.2	0.5

positive correlation observed between particulate emission factors and coal volatile content (15). However, because this observation was made on a narrow range of coal volatile content, it requires further study over a broader range of coal types for verification.

It is also suspected that burning coals with high free-swelling index may adversely affect particulate emission factors (15). High free-swelling index coals have a greater tendency to agglomerate, thereby creating conditions for incomplete combustion. This finding is also supported by the carbonaceous nature of particulate emissions and demonstrates the importance of combustion efficiency with respect to particulate emissions.

Sulfur Oxides

Sulfur oxide emission factors are presented in terms of coal sulfur content which is the limiting and single most important variable affecting the formation of SO_x. Typically, 70% of the coal sulfur content is emitted as gaseous sulfur oxides, as demonstrated in Figure 11 (15). The point falling above the maximum SO_x line (calculated SO_2 emissions based on coal sulfur content) is in error either in emission rate determination on in coal sulfur content determination. The low SO_x emission factor for the 1.5% sulfur coal may be the result of calcium in the coal combining with the sulfur, thereby reducing the formation of SO_x. The 1.5% sulfur coal was found to contain 50% more calcium than the 1% sulfur coal from the same study.

Nitrogen Oxides

Emissions of nitrogen oxides are dependent on many variables related to the combustion process, and extensive testing would be required to determine the effect of these variables on NO_x emission rates. At the low combustion temperatures attained in residental combustion (<1,800°K), 60% to 100% of the NO_x emitted

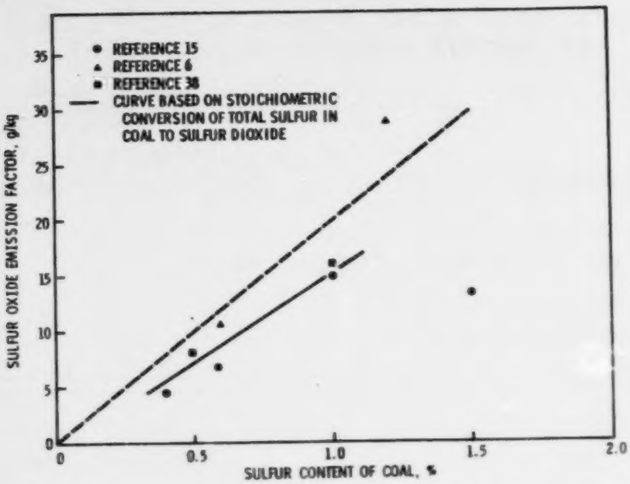

Figure 11. Effect of coal sulfur content on SO_x emissions.

is formed from fuel nitrogen, and the remaining nitrogen is provided by combustion air (45). Most of the NO_x emissions are in the form of nitric oxide (NO); nitrogen dioxide (NO_2) accounts for the remainder.

Hydrocarbons

Measurement of hydrocarbon emissions from coal-fired residential combustion equipment has been limited to units burning bituminous coal (15, 30, 38, 39). In addition, hydrocarbon collection techniques employed in the cited studies have differed somewhat from each other, although most rely on condensation of organic material in traps held below 0°C. These techniques collect the higher molecular weight hydrocarbons but allow the lower molecular weight ones to pass through. One study employed a hydrocarbon measurement technique (flame ionization) that also measured low molecular weight hydrocarbons (38). Emission factors determined from these measurements were of the same magnitude as those determined from the condensation technique indicating that condensation collects a substantial portion of the hydrocarbon species emitted. However, the lack of more complete emission data on lower molecular weight hydrocarbon emissions prevent any definite conclusion as to the actual total hydrocarbons emitted from coal-fired residential combustion. Based on the available data, the condensation techniques probably accounts for at least 50% of the total hydrocarbons. In addition, many of the environmentally significant hydrocarbons such as POM compounds have been collected and quantified by the condensation techniques. The addition of a porous polymer trap improves the collection efficiency of these compounds (6, 15).

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(45) Vogt, R. A., and N. M. Laurendeau. Nitric Oxide Formation in Pulverized Coal Flames. PURDU-CL-76-08 (PB 263 277), National Science Foundation, Washington, D.C., September 1967. 92 pp.

Hydrocarbon emissions appear most affected by combustion equipment. The average hydrocarbon emission factor for the hand-fed units tested (including fireplaces) was about five times higher than the average from stoker-fed units. Because hydrocarbon emissions are a result of incomplete combustion, this difference can be explained by comparing the natures of hand-fed combustion (overfeed) and stoker-fed combustion (underfeed), described in detail in Section 3. Hydrocarbon emissions species have been characterized by collection on a polymeric resin, designed for organic material entrapment, and subsequent analysis by a gas chromatograph/mass spectrometer (GC/MS) (15).

Table 18 lists the more than 50 organic compounds identified in one test program (15). The emission factors for each species are also provided. These emission factors represent the average of results from a test on a coal-fired boiler and a test on a coal-fired furnace. The analysis of a coal tar sample, performed by MRC for a commercial customer in another program, is presented in Table 19 for comparison. As noted, the tar from a coal gasification process is very similar in composition to the organic material condensed from the flue gas generated in residential coal combustion. These results support the conclusion that residential coal combustion is incomplete and that coal volatiles are vaporized, escaping into the atmosphere unburned.

Carbon Monoxide

Emissions of carbon monoxide from coal-fired residential combustion equipment are highly variable, ranging from <0.04 g/kg to 69 g/kg. These values are high compared to those for larger coal-fired industrial and utility boilers [0.5 g/kg to 1.0 g/kg (40)], indicating a lower combustion efficiency for the residential units. This occurs in spite of the high excess-air levels frequently found in residential combustion. The best explanation for poorer residential combustion performance is found in the geometry of the fuel combustion unit. Unlike larger utility boilers where coal is pulverized and burned as small discrete particles suspended in a high-temperature gas stream, residential-size units burn coal in a pile which can have many pockets of incomplete combustion caused by localized oxygen deficiencies. As expected, the highest level of CO emissions was observed from hand-fed units (38, 39).

TABLE 18. MAJOR ORGANIC SPECIES EMITTED FROM RESIDENTIAL COMBUSTION OF BITUMINOUS COAL (15)

Identified compound	Average[a] emission factor, g/kg
C_3-alkylbenzenes	0.022[b]
C_4-alkylbenzenes	0.010[b]
Indane	0.001
Methylindenes	0.015[b]
Phenol	0.042
Methyl phenol	0.055
Dimethyl phenol	0.041[b]
C_3-alkyl phenol	0.009[b]
Naphthalene	0.15
Methylnaphthalenes	0.12
Dimethylnaphthalenes	0.11
C_3-alkylnaphthalenes	0.057
C_4-alkylnaphthalenes	0.017
C_5-alkylnaphthalenes	0.007
Biphenyl	0.006
Acenaphthene	0.039
Fluorene	0.026
Methylfluorene	0.016
Phenyl phenol	0.002[b]
Benzofuran	0.002[b]
Methylbenzofuran	0.01
Fluorenone	0.011
Di-t-butyl cresol	0.008[b]
Methyl resorcinols	0.05[b]
Anthraquinone	0.003[b]
Methyl laurate	0.001[b]
Methyl myristate	0.001[b]
C_{11}-alkyl phenol	0.003[b]
Methyl palmitate	0.003
Methyl stearate	0.002
Di-C_2-alkylphthalate	0.015[b]
Di-C_3-alkylphthalate	0.0007
Di-C_4-alkylphthalate	0.0008
Di-2-ethylhexylphthalate	0.01
Dioctylphthalate	0.076
Aliphatics (C_{14} to C_{33})	1.5
POM:	
Dibenzothiophene	0.0002
Anthracene/phenanthrene	0.016
Methylanthracenes/phenanthrenes	0.01
9-Methylanthracene	0.0002
Dimethylanthracenes/phenanthrenes	0.008
Fluoranthene	0.005
Pyrene	0.005
Methylfluoranthenes/pyrenes	0.003
Benzo(c)phenanthrene[c]	0.0002
Chrysene/benz(a)anthracene	0.004
7,12-Dimethylbenz(a)anthracene[c,d]	0.083
Benzofluoranthene(s)[c]	0.004
Benzopyrene(s) (and perylene)	0.003
3-Methylcholanthrene[d,c]	0.002
Indeno(1,2,3-cd)pyrene[c]	0.002
Dibenz(a,h)anthracene[d,c]	0.003
Dibenzo(c,g)carbazole[e]	<0.0001
Dibenzopyrenes[c]	0.009
Methylchrysenes[d,e]	0.005
C_4-alkylphenanthrene	0.002
Total	2.6

[a] Average of two samples.

[b] Only identified in one sample.

[c] These groups contain known carcinogens (46).

[d] May include isomers.

[e] Quantitation based on response of benzofluoranthene.

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(46) Biologic Effects of Atmospheric Pollutants - Particulate Polycyclic Organic Matter. National Academy of Sciences, Washington, D.C., 1972. 361 pp.

TABLE 19. ANALYSIS OF COAL TAR SAMPLE FROM COAL GASIFICATION PROCESS[a]

Organic species	Amount,[b] μg
Phenol	61
Methylphenols	281
Dimethylphenols	131
Trimethyl (or methylethyl) phenols	56
Methylindanes	12
Dimethylindanes	12
Methylbenzaldehydes	11
Dimethylbenzaldehydes	11
Naphthalene	23
Methylnaphthalenes	109
Dimethylnaphthalenes	172
Acenaphthene	115
Fluorene	202
Naphthols	101
Methyl naphthols	149
Dimethyl naphthols	80
Trimethylnaphthalenes	139
Benzofuran	40
Tetramethylnaphthalenes	13
Pentamethylnaphthalenes	13
Methylbenzofurans	76
Dimethylbenzofurans	48
Methylfluorenes	112
Trimethylbenzofurans	29
Anthracene/phenanthrene	128
Methylanthracenes/methylphenanthrenes	248
Dimethylanthracenes/dimethylphenanthrenes	95
Fluoranthene	33
Pyrene	32
Dibenzofurans	31
Methylfluoranthenes/methylpyrenes or benzofluorenes	176
Dimethylfluoranthenes/dimethylpyrenes	95
Methyldibenzofurans	109
Dimethyldibenzofurans	122
C_4-alkylanthracenes/C_4-alkylphenanthrenes	47
Benzo(c)phenanthrene	22
Chrysene/benz(a)anthracene	94
C_3-alkylfluoranthenes/C_3-alkylpyrenes	47
Methylbenzanthracenes (or isomers)	409
Cholanthrene	124
Dimethylbenzanthracenes (or isomers)	606
C_3-alkyldibenzofurans	53
Benzofluoranthenes	72
Benzopyrenes/benzoperylene	67
Methylcholanthrenes	220
Dibenzofluorenes	207
Dibenzanthracenes	35
Benzo(ghi)perylene	33
Dimethylcholanthrenes	143
Methyldibenzofluorenes	114
Methyldibenzanthracenes	75
Methylbenzo(ghi)perylenes	51
Dimethyldibenzanthracenes	50
C_3-alkyldibenzanthracenes	12
Dibenzopyrenes	92
Total	5,638

[a] In-house analysis performed by MRC for commercial customer in another program.

[b] Relative amounts found using gas chromatography/mass spectrometry.

POM and PCB

Emissions of polynuclear organic materials (POM's) from residential coal combustion are significant and should be of some concern. POM emission factors from coal-fired residential combustion are at least two orders of magnitude greater than those from larger combustion sources and other residential fossil-fuel units, as shown in Table 20 (2).

TABLE 20. POM EMISSION FACTORS FROM COAL-FIRED RESIDENTIAL COMBUSTION COMPARED TO OTHER COMBUSTION SOURCES (2)

Combustion source type	Approximate POM emission factor,[a] pg/J
Residential:	
Bituminous coal	1,900[b]
Gas	1.0
Oil	4.2
Commercial/Institution, coal	19
Industrial, coal	10
Utility, coal	0.8

[a] These values were derived from data in Reference 2 as explained in Appendix D.

[b] Value determined in this study.

POM formation during combustion is strongly dependent on combustion efficiency (47), which is known to vary widely, not only from unit to unit, but also within individual units. Conditions necessary for complete combustion of POM's are sufficient time for completion of chemical reactions, sufficient temperature to heat all of the fuel through its decomposition stages and to ignite it, and sufficient turbulence to thoroughly mix the combustible material and oxygen. In spite of high excess-air levels associated with residential combustion, nonuniform fuel beds and deviation from the above combustion criteria favor the formation of POM's. Excess air levels that are too high, although providing sufficient oxygen for complete combustion, also may favor POM formation by faster quenching in the post-flame region and by reducing retention times in the combustion chamber. Consequently, POM measurements within each test program are highly variable as shown in Table 16. In addition, the average POM emission factors for each test cover two orders of magnitude. This inverse relationship of POM formation to combustion efficiency accounts for the higher POM emission rates from hand-fed units and the OFF portion of a heating cycle (15). The effect of heating cycle on emissions is discussed later in this section.

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(47) Knierman, H., Jr. A Theoretical Study of PCB Emissions from Stationary Sources. Contract 68-02-1320, Task 26, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, September 1976. 38 pp.

Besides combustion equipment, coal parameters may also influence POM emissions. For example, an increase in POM emissions has been observed with increasing percent of volatile material in the coal (15). The supporting data cover a narrow range of coal volatile matter and, therefore, require further testing for confirmation.

Emissions of individual POM compounds from residential combustion of coal were presented in Table 18 for limited test conditions. About 65% (by mass) of the POM emissions were known carcinogens, indicating the carcinogenic nature of the POM emission factor developed in this study.

Polychlorinated biphenyls (PCB's) were not found in the emissions from a residential bituminous coal-fired unit and were not tested in anthracite and lignite combustion. Based on the sensitivity of the analytical technique (GC/MS), PCB compounds, if present, are emitted at less than 5 μg/kg of coal (15).

Individual Elements

Emissions of individual elements from the residential combustion of two bituminous coals have been measured, and results are presented in Table 21 (15). Because of the high variability in coal elemental content, these emission factors cannot be used to represent emissions from the whole population. Emission factors for individual elements, however, were used to estimate the fraction of specific elements present in coal that is emitted to the air upon combustion. This fraction was then applied to an average coal elemental composition to predict average emission factors for individual elements. The emission data suggest that the upper limit of the emission factor for each nonvolatile element is about 10% of the concentration of that element in coal. The actual value in most cases is probably less than 5%, but there are insufficient supportive data to prove this.

Table 22 lists the elemental emission species that were evaluated and gives each one's fraction of coal content estimated to be emitted upon combustion. This fraction times the concentration of that element in the three average coal types (Table 9, 10, and 11) was used to calculate the emission factors presented in Table 14.

TABLE 21. EMISSION FACTORS FOR INDIVIDUAL ELEMENTS FROM BITUMINOUS COAL-FIRED RESIDENTIAL HEATING EQUIPMENT (15)

(g of pollutant/kg of fuel)

Element emitted	Residential boiler burning Utah bituminous coal	Residential furnace burning Wyoming bituminous coal
Aluminum	0.007	0.085
Antimony	<0.0005[a]	<0.016[a]
Arsenic	0.0004	0.001
Barium	0.0003	0.007
Boron	0.002	0.017
Cadmium	<0.002[a]	<0.0004[a]
Calcium	0.012	0.16
Chromium	<0.005[a]	0.002
Cobalt	<0.0005[a]	<0.0005[a]
Copper	<0.0005[a]	0.003
Iron	0.017	0.1
Lead	<0.003[a]	<0.007[a]
Magnesium	0.002	0.047
Manganese	0.0003	0.001
Mercury	0.0001	0.0003
Molybdenum	<0.0001[a]	<0.02[a]
Nickel	0.00005	<0.02[a]
Phosphorus	<0.009[a]	<0.014[a]
Selenium	<0.002[a]	0.0005
Silicon	0.002	0.09
Silver	<0.0005[a]	<0.033[a]
Sodium	0.009	<0.006[a]
Strontium	<0.0004[a]	0.002
Tin	0.003	<0.037[a]
Titanium	0.002	0.007
Vanadium	<0.002[a]	0.003
Zinc	0.003	0.014

[a] Value is based on the detection limit.

TABLE 22. FRACTION OF ELEMENTS IN COAL EMITTED TO THE ATMOSPHERE DURING RESIDENTIAL COMBUSTION

Emission species	Fraction of coal content emitted to air, %	Basis[a]	Reference
Aluminum	10	A	15
Antimony	75	B	48-51
Arsenic	75	A, B	15, 48-51
Barium	10	A	15
Beryllium	10	C	48-51
Bismuth	10	B	48-51
Boron	10	C	
Bromine	100	B	48-51
Cadmium	75	B	48-51
Calcium	10	A	15
Chlorine	100	B	48-51
Chromium	10	A	15
Cobalt	10	A, B	15, 48-51
Copper	10	A	15
Fluorine	100	B	48-51
Gallium	75	B	48-51
Iron	10	A	15
Lead	75	B	48-51
Lithium	10	C	
Magnesium	10	A	15
Manganese	10	A	15
Mercury	100	A, B	15, 48-51
Molybdenum	75	A, B	15, 48-51
Nickel	10	B	48-51
Niobium	10	B	48-51
Phosphorus	10	A	15
Potassium	10	B	48-51
Scandium	10	B	48-51
Selenium	75	B	48-51
Silicon	10	B	48-51
Silver	50	C	
Sodium	10	B	48-51
Strontium	10	A	15
Tellurium	50	C	
Thallium	75	B	48-51
Thorium	10	B	48-51
Tin	10	B	48-51
Titanium	10	A	15
Uranium	10	B	48-51
Vanadium	10	A	15
Ytterbium	10	C	
Yttrium	10	B	48-51
Zinc	75	B	48-51
Zirconium	10	B	48-51

[a] A = Estimate based on sampling data from western bituminous coal.

B = Estimate based on partitioning behavior in larger combustion units.

C = Estimate based on position of element in periodic table relative to other elements of known partitioning behavior.

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(48) McCurley, W. R., R. B. Reznik, and J. Ochsner. Source Assessment: Pulverized Bituminous Coal-Fired Dry Bottom Industrial Boilers. Contract 68-02-1874, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. (Unpublished draft report prepared by Monsanto Research Corporation, May 1978.)

(continued)

Elements not accurately characterized in Reference 15 were determined from other references based on their general partitioning behavior presented in Table 23 (48-51). Elements expected to be largely volatilized during combustion were assumed to be 100% emitted as an upper limit, while those elements expected to concentrate in fly ash because of partial volatilization and subsequent condensation were assigned an upper limit of 75%.

TABLE 23. CLASSIFICATION OF ELEMENTS ACCORDING TO THEIR PARTITIONING BEHAVIOR (49-51)

Partitioning class	Elements
Class I - Elements equally distri- between bottom and fly ash	Aluminum, barium, bismuth, calcium, cobalt, iron, magnesium, manganese, niobium, potassium, scandium, silicon, strontium, thorium, tin, titanium, yttrium, zirconium
Class II - Elements concentrating in fly ash	Antimony, arsenic, cadmium, copper, gallium, lead, molybdenum, selenium, thallium, zinc
Class III - Elements remaining in gas phase	Bromine, chlorine, fluorine, mercury
Elements intermediate between Classes I and II	Chromium, nickel, sodium, uranium, vanadium

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(continued)

(49) Davison, R. L., D. F. S. Natusch, J. R. Wallace, and C. A. Evans, Jr. Trace Elements in Fly Ash - Dependence of Concentration on Particle Size. Environmental Science and Technology, 8(13):1107-1113, 1974.

(50) Kaakinen, J. W., R. M. Jorden, M. H. Lawasani, and R. E. West. Trace Element Behavior in Coal-Fired Power Plant. Environmental Science and Technology, 9(9):862-869, 1975.

(51) Klein, D. H., A. W. Andren, J. A. Carter, J. F. Emery, C. Feldman, W. Fulkerson, W. S. Lyon, J. C. Ogle, Y. Talmi, R. I. VanHook, and N. Bolton. Pathways of Thirty-Seven Trace Elements Through Coal-Fired Power Plant. Environmental Science and Technology, 9(10):973-979, 1975.

Emissions Affected by Operating Cycle

Automatic coal-fired heating equipment differs from other forms of automatic heating in that a bed of fuel continued to burn when the demand for heat is satisfied and the combustion-air fan shuts off. Consequently, the equipment continues to release pollutants to the atmosphere during the OFF period. However, combustion and the flue gas composition are not the same as during the ON period.

Two test programs have investigated emissions from each cycle segment for bituminous coal combustion (6, 15); however, results from Reference 6 are not discussed here because of the atypical operation of the barometric damper. Both studies indicate that variations in the ON/OFF cycle can alter the overall emission factors.

Table 24 presents a comparison of average emission data obtained from each cycle segment during testing of a bituminous coal-fired warm-air furnace (15). Emission rates are presented rather than emission factors because it was impossible to measure separately the actual quantity of coal burned during the ON and OFF segments of the heating cycle.

Emission rates for all emission species were higher during the ON segment except for POM emissions which were about three times higher in the OFF segment. Because POM emissions are products of incomplete combustion of volatiles, this finding was not unexpected. Carbon monoxide is also a product of incomplete combustion and should be generated in the largest amounts during the OFF period when insufficient oxygen exists for stoichiometric combustion. This relationship was seen in Reference 6, but the opposite condition occurered in Reference 15.

The difference in CO emission rates cannot be fully explained, although the operation of the barometric damper may be the key to any logical explanation. The position of the barometric damper can play an important role in determining the nature and extent of combustion during the OFF segment. In Reference 15, sampling was conducted with the barometric damper free to open and close when the stack pressure drop varried as it would in actual operation. As a result, a minimum amount of draft was induced through the combustion chamber. In contrast, sampling in Reference 6 was conducted with the barometric damper fixed closed. Draft induced in the exhaust stack thus pulled air through the combustion chamber, causing residual fuel to burn more rapidly. It might be expected, therefore, that this higher combustion rate during the OFF segment generated more CO than when the damper was allowed to open, because a greater quantity of coal burned at less than desirable combustion conditions.

TABLE 24. AVERAGE EMISSION RATES FOR A 20-MINUTE ON AND 40-MINUTE OFF HEATING CYCLE OF A RESIDENTIAL BITUMINOUS COAL-FIRED COMBUSTION UNIT (15)
(g/hr[a])

Emission species	Heating cycle segment ON	Heating cycle segment OFF
Particulates	83	16
SO_x	76	4.5
NO_x	28	5
CO	58	14
POM	0.026	0.077
Condensable organics	13	6
Elements:		
Aluminum	0.39	0.12
Antimony	<0.022[b]	<0.054[b]
Arsenic	0.009	0.003
Barium	0.025	0.009
Boron	0.068	0.023
Cadmium	<0.0003[b]	<0.002[b]
Calcium	0.82	0.059
Chromium	0.008	0.0095
Cobalt	0.003	0.005
Copper	0.014	<0.001[b]
Iron	0.59	0.068
Lead	<0.007[b]	<0.037[b]
Magnesium	0.29	0.016
Manganese	0.007	<0.0005[b]
Mercury	<0.00003[b]	0.002
Molybdenum	<0.038[b]	<0.014[b]
Nickel	<0.022[b]	0.059
Phosphorus	<0.031[b]	<0.032[b]
Selenium	0.003	<0.005[b]
Silicon	0.19	0.23
Silver	<0.12[b]	<0.030[b]
Sodium	0.054	<0.024[b]
Strontium	0.011	<0.001[b]
Tin	<0.095[b]	<0.15[b]
Titanium	0.044	<0.005[b]
Vanadium	0.006	0.006
Zinc	0.073	<0.009[b]

[a] Emissions are presented as kilograms per hour rather than grams per kilogram because quantifying the amount of coal combusted during each cycle segment was not possible.

[b] Value is based on the detection limit.

Emissions data from Reference 15 were determined for heating equipment operating at a 20-min ON/40-min OFF heating cycle. This cycle was determined to be representative of the average total ON and total OFF time for a heating season (see Appendix A). Furnaces controlled by thermostat may have ON/OFF cycles of shorter duration. Extrapolation of the data to predict emissions for other heating cycles is possible if the emission rates are not strongly dependent on the length of the ON and OFF periods. Although variations in the heating cycle were not studies, it is believed that conditions during the ON and OFF periods approximate steady-state conditions. Emission factors for the lower percentages of ON time are representative of the early and late parts of the heating season while the emission factors for high percentages of ON time represent the coldest part of the heating season.

SOLID RESIDUES

Combustion of coal in residential heating equipment produces a solid residue consisting of inorganic material (coal ash) and unburned or partially burned coal. The following discussion is based on the quantification and characterization of solid residues from a boiler and warm-air furnace burning high volatile bituminous coal (15).

Ash Quantification

The coal-fired boiler studied had no provisions for physical separation of ash from fuel, and any attempt to quantitatively recover ash resulted in removal of partially burned coal from the fuel bed or incomplete recovery of ash. A fused mass of ash removed from the boiler included pieces of partially combusted coal. The coal-fired warm-air furnace was equipped with a slide-out ash pan located below the fuel bed which permitted recovery and quantification of solid residue.

Quantities of ash residue recovered from the combustion of bituminous coal in the warm-air furnace are listed in Table 25 as grams of residue per kilogram of coal burned. Because the amount of residue is greater than the ash content of the coal, the combustion process must be incomplete, with unburned coal dropping into the ash pan. Three samples of residue were analyzed and found to contain from 15% to 56% unburned coal, or 44% to 85% actual ash. This accounts for the high variability of residue recovery.

Because no other coals were tested, the representativeness of these results is unknown. However, it can be assumed that different results will be obtained from burning other grades of coal or using different combustion equipment where agglomerating tendencies and combustion efficiencies differ.

TABLE 25. ASH RESIDUE FROM COMBUSTION OF BITUMINOUS COAL IN A WARM-AIR FURNACE (15) (g/kg)

Test number	Coal ash content	Average ash residue
13	50	300
14	50	121
17	91	155
18	91	149
22	91	118
25	71	110

Elemental Composition

Elements present in coal burned in residential heating equipment which are not emitted in the flue gas remain in the solid residue either as unburned coal or nonvolatilized inorganic ash. The elemental composition of this material is presented in Table 26 for residue from a warm-air furnace burning bituminous coal (15).

TABLE 26. CONCENTRATION OF ELEMENTS IN THE ASH RESIDUE FROM A BITUMINOUS COAL-FIRED WARM-AIR FURNACE (15)

Element	Average[a] concentration in residue, %
Aluminum	3.4
Antimony	0.016
Arsenic	0.001
Barium	0.084
Boron	0.012
Cadmium	0.0007
Calcium	2.6
Chromium	0.018
Cobalt	0.009
Copper	0.034
Iron	2.7
Lead	0.012
Magnesium	0.83
Manganese	0.029
Mercury	<0.0000004[b]
Molybdenum	0.004
Nickel	0.025
Phosphorus	0.17
Selenium	0.005[c]
Silicon	0.011
Silver	0.017
Sodium	0.13
Strontium	0.075
Tin	0.007
Titanium	0.3
Vanadium	0.034
Zinc	0.016

[a] Average of two samples.

[b] Value is based on the detection limit.

[c] Value is that of the reagent blank used as upper limit.

POTENTIAL WATER POLLUTANTS

The elemental content of ash residue may be an environmental problem if the ash is exposed to rainfall and elements in the ash leach out and enter water supplies. A test was conducted on residue from a warm-air furnace to estimate the relative leachability of elements from coal-fired residential combustion residue (15). Ash was shaken for 24 hours in distilled water at an ash-to-water ratio of 1 to 10, and the elemental content of the water was determined after shaking. Final pH of the water rose to 11.6 from an initial pH of 7.1, reflecting the alkalinity of the ash and high calcium content of the coal.

Relative leachability of the elements found in ash residue is presented in Table 27 as grams leached per kilogram of ash and as percent of element leached from ash (15). About half of the elements were found to be below the detection limits, corresponding to leaching of less than 0.001 g/kg; some values were as low as less than 0.0001 g/kg.

TABLE 27. RELATIVE LEACHABILITY OF INDIVIDUAL ELEMENTS FROM COAL-FIRED RESIDENTIAL COMBUSTION RESIDUE (15)

Element	Amount leached per quantity of ash, g/kg	Fraction of element in ash leached to water, %
Aluminum	0.012	0.035
Antimony	<0.002	<0.13
Barium	0.019	2.3
Boron	0.002	1.9
Cadmium	<0.00005	<0.77
Calcium	5.8	23
Chromium	<0.00002	<0.011
Cobalt	<0.0001	<0.12
Copper	<0.0001	<0.029
Iron	<0.00001	<0.00004
Lead	<0.0005	<0.42
Magnesium	0.002	0.024
Manganese	<0.00001	<0.004
Mercury	<0.00002	<92
Molybdenum	0.001	2.0
Nickel	<0.0005	<0.20
Phosphorus	<0.001	<0.059
Selenium	0.0003	74
Silicon	0.047	45
Silver	<0.0004	<0.23
Sodium	1.2	91
Strontium	0.15	20
Tin	<0.0004	<0.62
Titanium	<0.00002	<0.0007
Vanadium	<0.00005	<0.015
Zinc	<0.00002	<0.013

Although this type of test may be considered a worst case because it does not address the rate of leaching, it is indicative of the types of material that can be leached in the greatest quantity.

POTENTIAL ENVIRONMENTAL EFFECTS

Air emissions from coal-fired residential combustion sources have their greatest potential environmental effect when at the maximum ground level concentration. Unlike larger combustion systems (i.e., utility boilers) which have tall stacks to disperse emissions and reduce ground level concentrations, residential units release emissions close to ground level where dispersion is minimal. Although the maximum ground level concentration from a single emission source may be relatively high, its distance from the emission point is such that few people are exposed to that concentration.

Unique to residential combustion, however, is the potential for multiple sources such as in a housing subdivision. In this case, emissions from many coal-fired heating devices have an additive effect that increases the maximum ground level concentrations and covers more land area with a high population density. The potential environmental effects of air emissions from coal-fired residential combustion systems were evaluated using source severity, affected population, state emission burdens, and national emission burdens as discussed below.

Source Severity

Source severity, S, measures the potential health effect of an emission species at its maximum ground level concentration and is expressed as the following ratios:

$$S = \frac{\bar{\chi}_{max}}{F} \tag{1}$$

where $\bar{\chi}_{max}$ = the time-averaged maximum ground level concentration for each emission specie

F = hazard factor = ambient air quality standard (AAQS) for criteria pollutants (particulates, hydrocarbons, NO_x, SO_x, and CO) and TLV(8/24)(1/100)[a] for noncriteria pollutants

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[a] 8/24 = correction factor to adjust the TLV to a 24-hr exposure level.

1/100 = safety factor.

The values of $\overline{\chi}_{max}$ were computed from the equation suggested by Turner (52):

$$\overline{\chi}_{max} = \chi_{max} \left(\frac{t_o}{t}\right)^{0.17} \qquad (2)$$

where χ_{max} is the "instantaneous" (i.e., 3-min average) maximum ground level concentration as determined for class C stability from the equation:

$$\chi_{max} = \frac{2\ Q}{\pi e u H^2} \qquad (3)$$

where Q = emission rate, g/s

H = emission height, m

π = 3.14

e = 2.72

u = wind speed, m/s
= 4.5 m/s (national average)

t_o = 3 min

t = averaging time, min

Detailed derivations of the severity equations are presented in Appendix E.

Tables 28 (53) and 29 (54) list the ambient air quality standards used for criteria pollutants and the TLV's used for noncriteria pollutants. Emission factors used for the severity calculations were those presented in Table 14. Severities were determined for the three average source types described in Section 3; results are presented in Table 30. Only POM emissions had severities in excess of 0.05.

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(52) Turner, D. B. Workbook of Atmospheric Dispersion Estimates. Public Health Service Publication 999-AP-26, U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio, May 1970. 84 pp.

(53) Code of Federal Regulations, Title 42 - Public Health, Chapter IV - Environmental Protection Agency, Part 410 - National Primary and Secondary Ambient Air Quality Standards, April 28, 1971. 16 pp.

(54) TLVs® Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1976. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1976. 94 pp.

TABLE 28. AMBIENT AIR QUALITY STANDARDS FOR CRITERIA POLLUTANTS (53)

Emission	Ambient air quality standard, mg/m^3
Particulate	0.260
NO_x	0.100
SO_x	0.365
CO	40.0
Hydrocarbons	0.160[a]

[a] There is no primary ambient air quality standard for hydrocarbons. The value of 160 $\mu g/m^3$ used for hydrocarbons in this report is a recommended guideline for meeting the primary ambient air quality standard for oxidants.

Because residential combustion of coal is usually scattered sparsely throughout the population or in rural locations, severity for a single emission point adequately represent present residential coal combustion. However, it is known that, at least in isolated areas, groups of residential structures are or will be equipped with coal-fired heating equipment (12, 55). The environmental effects from such multiple sources will be greater than from single sources because of the potential for plume overlap to increase the ground level concentration in densely populated areas (55).

A modification of the dispersion model used for single point severity has been employed to predict the maximum ground level concentrations of emissions from an array of 100 houses equipped

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(55) Cart, E. N., Jr., M. H. Farmer, C. E. Jahnig, M. Lieberman, and F. M. Spooner. Evaluation of the Feasibility for Widespread Introduction of Coal into the Residential and Commercial Sectors -- Volume I - Executive Summary. Council of Environmental Quality, Washington, D.C., August 1977. 32 pp.

TABLE 29. THRESHOLD LIMIT VALUES USED FOR NONCRITERIA POLLUTANTS (54)

Emission species	TLV, mg/m^3	Compound used for TLV
POM (carcinogenic)	0.001	Carcinogen[a]
Polychlorinated biphenyls	0.5	Chlorodiphenyl (54% chlorine) - skin
Elements:		
Aluminum	10	Alundum, Al_2O_3
Arsenic	0.5	Arsenic and compounds
Antimony	0.5	Antimony and compounds
Barium	0.5	Barium (soluble compounds)
Beryllium	0.002	Beryllium
Bismuth	10	–[b]
Boron	10	Boron oxide
Bromine	0.7	Bromine
Cadmium	0.05	Cadmium oxide fume
Calcium	5	Calcium oxide
Chlorine	7.0	Hydrogen chloride
Chromium	0.1	Chromic acid and chromates
Cobalt	0.1	Cobalt metal, dust, and fume
Copper	1	Copper, dusts, and mists
Fluorine	2	Fluorine
Gallium	10	–[b]
Iron	5	Iron oxide fume
Lead	0.15	Lead, inorganic fumes, and dusts
Lithium	10	–[b]
Magnesium	10	Magnesium oxide fume
Manganese	5	Manganese and compounds
Mercury	0.05	All forms except alkyl
Molybdenum	5	Soluble compounds
Nickel	0.1	Soluble compounds
Niobium	0.5	Vanadium[c]
Phosphorus	1	Phosphoric acid
Potassium	2	Potassium hydroxide
Scandium	10	–[b]
Selenium	0.2	Selenium compounds
Silicon	10	Silicon
Silver	0.01	Metal and soluble compounds
Sodium	2	Sodium hydroxide
Strontium	10	–[b]
Tellurium	0.1	Tellurium
Thallium	0.1	Thallium soluble compounds
Thorium	0.2	Uranium[c]
Tin	10	Tin oxide
Titanium	10	Titanium dioxide
Uranium	0.2	Soluble and insoluble compounds
Vanadium	0.5	Vanadium pentoxide dust, V_2O_5
Ytterbium	10	–[b]
Yttrium	1	Yttrium
Zinc	5	Zinc oxide fume
Zirconium	5	Zirconium compounds

[a] Value for carcinogenic compounds corresponds approximately to the minimum detectable limit; all POM compounds may not be carcinogenic.

[b] For elements not having an approximate TLV, the TLV for nuisance particulate, 10 mg/m^3, was used.

[c] No TLV found for emission species; used TLV of closely related compound based on toxicity.

TABLE 30. SOURCE SEVERITIES FOR EMISSIONS FROM AVERAGE, AUTOMATIC, COAL-FIRED RESIDENTIAL COMBUSTION UNITS[a] a

Emission species	Source severity[b]		
	Bituminous	Anthracite	Lignite
Particulates	3.0×10^{-3}	7.0×10^{-4}	1.0×10^{-2}
SO_x	2.0×10^{-2}	4.0×10^{-3}	1.0×10^{-2}
NO_x	9.0×10^{-3}	2.0×10^{-3}	1.0×10^{-2}
Hydrocarbons	2.0×10^{-3}	2.0×10^{-3}	1.0×10^{-3}
CO	7.0×10^{-6}	5.0×10^{-5}	1.0×10^{-5}
Polycyclic organic materials	2.6	5.0×10^{-2}	
Polychlorinated biphenyls	$<4.5 \times 10^{-7}$		
Formaldehyde	2.0×10^{-5}		
Elements:			
Aluminum	7.0×10^{-3}	1.0×10^{-2}	3.0×10^{-3}
Antimony	7.0×10^{-5}	7.0×10^{-5}	3.0×10^{-5}
Arsenic	2.0×10^{-3}	4.0×10^{-4}	7.0×10^{-4}
Barium	9.0×10^{-4}	1.0×10^{-3}	6.0×10^{-3}
Beryllium	5.0×10^{-3}	5.0×10^{-3}	7.0×10^{-4}
Bismuth	5.0×10^{-8}	5.0×10^{-8}	
Boron	1.0×10^{-5}	5.0×10^{-5}	8.0×10^{-5}
Bromine	7.0×10^{-4}	7.0×10^{-5}	
Cadmium	5.0×10^{-4}	7.0×10^{-4}	1.0×10^{-4}
Calcium	1.0×10^{-3}	1.3×10^{-2}	2.0×10^{-2}
Chlorine	5.0×10^{-3}	1.0×10^{-3}	2.0×10^{-3}
Chromium	9.0×10^{-4}	1.0×10^{-3}	1.0×10^{-4}
Cobalt	3.0×10^{-4}	3.0×10^{-4}	7.0×10^{-5}
Copper	1.0×10^{-4}	1.0×10^{-4}	3.0×10^{-5}
Fluorine	2.0×10^{-3}	2.0×10^{-3}	9.0×10^{-4}
Gallium	2.0×10^{-5}	3.0×10^{-5}	5.0×10^{-6}
Iron	2.0×10^{-2}	4.0×10^{-3}	2.0×10^{-2}
Lead	3.0×10^{-3}	2.0×10^{-3}	1.0×10^{-3}
Lithium	1.0×10^{-5}	2.0×10^{-5}	1.0×10^{-6}
Magnesium	3.0×10^{-4}	3.0×10^{-4}	2.0×10^{-3}
Manganese	6.0×10^{-4}	2.0×10^{-5}	7.0×10^{-5}
Mercury	2.0×10^{-4}	2.0×10^{-3}	1.0×10^{-4}
Molybdenum	2.0×10^{-5}	1.0×10^{-5}	2.0×10^{-5}
Nickel	7.0×10^{-4}	1.0×10^{-3}	1.0×10^{-4}
Niobium	2.0×10^{-6}	1.0×10^{-6}	1.0×10^{-6}
Phosphorus	4.0×10^{-4}	4.0×10^{-4}	2.0×10^{-3}
Potassium	5.0×10^{-3}	6.0×10^{-3}	7.0×10^{-4}
Scandium	2.0×10^{-6}	2.0×10^{-6}	7.0×10^{-7}
Selenium	8.0×10^{-4}	7.0×10^{-4}	2.0×10^{-4}
Silicon	1.0×10^{-2}	1.0×10^{-2}	6.0×10^{-3}
Silver	5.0×10^{-5}	5.0×10^{-3}	5.0×10^{-3}
Sodium	7.0×10^{-4}	1.0×10^{-3}	1.0×10^{-2}
Strontium	5.0×10^{-5}	5.0×10^{-5}	2.0×10^{-4}
Tellurium	5.0×10^{-5}	3.0×10^{-5}	
Thallium	3.0×10^{-5}	2.0×10^{-3}	
Thorium	2.0×10^{-6}	1.0×10^{-6}	3.0×10^{-6}
Tin	9.0×10^{-7}	5.0×10^{-7}	3.0×10^{-7}
Titanium	4.0×10^{-4}	7.0×10^{-4}	2.0×10^{-4}
Uranium	2.0×10^{-5}	5.0×10^{-5}	2.0×10^{-5}
Vanadium	2.0×10^{-4}	2.0×10^{-4}	6.0×10^{-5}
Ytterbium	5.0×10^{-7}	5.0×10^{-7}	1.0×10^{-7}
Yttrium	5.0×10^{-5}	5.0×10^{-5}	2.0×10^{-5}
Zinc	1.0×10^{-4}	1.0×10^{-4}	3.0×10^{-5}
Zirconium	5.0×10^{-5}	5.0×10^{-5}	1.0×10^{-5}

[a] Blanks indicate data not available.

[b] Emissions assumed constant over a 24-hr period during the heating season.

with coal-fired heating equipment (56). Figure 12 illustrates the housing arrangement based on the highest expected concentration of houses. Determination of ground level concentrations differs somewhat from that just discussed for single point sources in that a wind speed of 1.0 m/s and stability class D were chosen to represent atmospheric conditions (versus national average conditions of 4.5 m/s and class C used in this report).

Ambient concentration profiles for the conditions chosen are presented in Figure 13 as a normalized isopleth diagram applicable to all pollutants (56). The curves are presented as percentages of the maximum ground level concentrations of the pollutants. From Figures 12 and 13, it can be seen that maximum concentration occurs at about 0.1 km downwind of the residential sources. Most of the 100 sources contribute to the maximum concentration, although the greatest contribution is from those sources immediately upwind. Further, relatively high concentrations occur within the residential array (56).

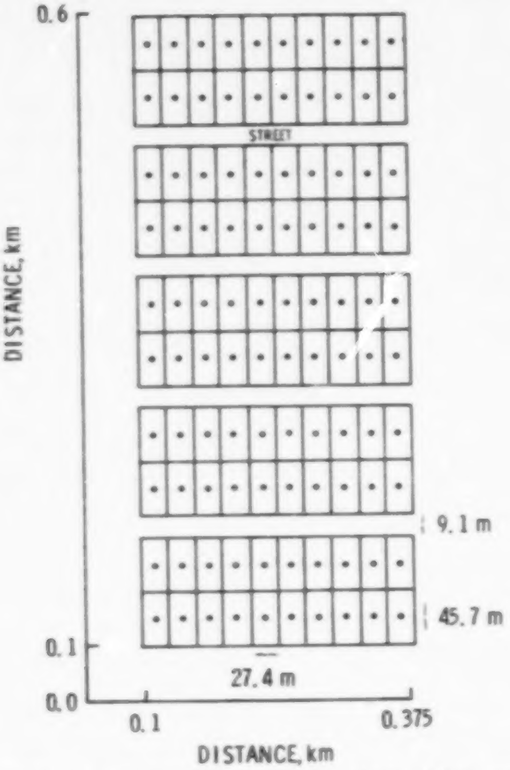

Figure 12. Housing arrangement for the evaluation of multiple residential coal-fired sources (56).

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(56) Weber, R. C. Impact on Local Air Quality from Coal-Fired Residential Furnaces. Masters Thesis, University of North Carolina, Chapel Hill, North Carolina, 1978. 88 pp.

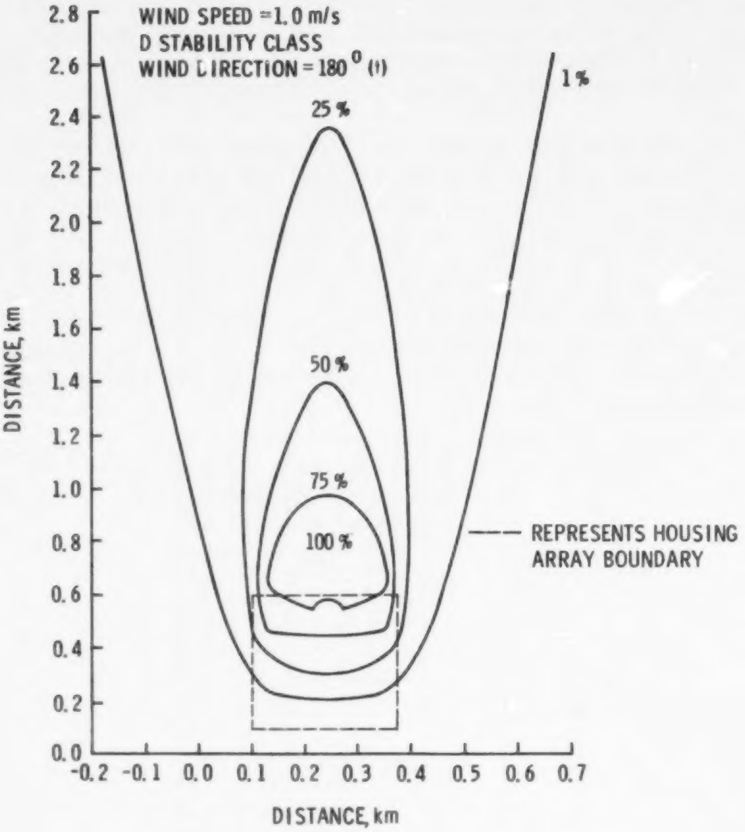

Figure 13. Isopleth diagram representing ambient concentration profiles as percent of maximum (56).

The model used in Reference 56 shows a direct proportional response for mass emission rates if all sources are adjusted simultaneously. For example, if the mass emission rate is doubled for all sources, the estimated ambient concentration also doubles. Therefore, if the mass emission rate and maximum ground level concentration for a particular pollutant are known, the following relationship can be used to calculate the maximum ground level concentration for any pollutant emission rate from the same array of sources (56):

$$\bar{\chi}_{max,i} = \bar{\chi}_{max,o} (Q_i)/Q_o \tag{4}$$

where $\overline{\chi}_{max,i}$ = average maximum ground level concentration of species i, g/m^3
$\overline{\chi}_{max,o}$ = average maximum ground level concentration for known reference species as determined by model, g/m^3
Q_i = mass emission rate for species i, g/s
Q_o = mass emission rate of reference species, g/s

This relationship can be used to determine the maximum ground level concentration of pollutants from an array of sources that differs uniformly from the original array as long as it differs only in mass emission rate and not in other pertinent parameters such as stack height. The emission sources used in Reference 56 are identical to the average sources used in this study except for fuel feed rate and average emission factors. Both of these parameters affect mass emission rate only and therefore allow Equation 4 to be used to determine the maximum ground level concentration for each average source type from the pollutant emission rate and the ratio of $\overline{\chi}_{max,o}/Q_o = 0.0172$ from Reference 56. Once $\overline{\chi}_{max}$ has been calculated from Equation 4, it can be used in Equation 1 to calculate the severity for 100 houses burning coal.

Table 31 presents the source severities for multiple residential sources burning bituminous, anthracite, and lignite coals. Values are about 30 times higher than the severities for a single source.

Affected Population

In addition to source severity, it is important to know how many people around an average residential combustion unit are exposed to high ground-level concentrations. Dispersion equations predict that the average ground level concentration ($\overline{\chi}$) varies with the distance (x) away from a source. For elevated sources, $\overline{\chi}$ is zero at the source, increases to some maximum value, $\overline{\chi}_{max}$, as x increases, and then falls back to zero as x approaches infinity. Therefore, a plot of $\overline{\chi}$/F versus x will have the appearances shown in Figure 14.

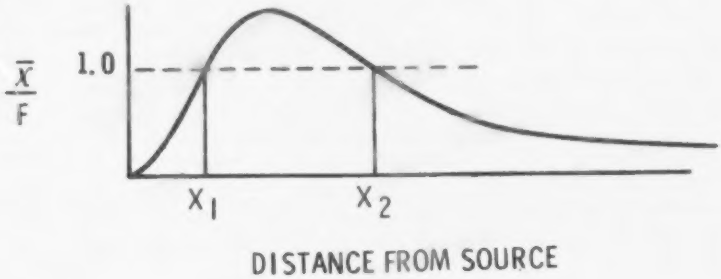

Figure 14. Variation of $\overline{\chi}$/F with distance.

TABLE 31. SOURCE SEVERITIES FOR COAL-FIRED RESIDENTIAL COMBUSTION EMISSIONS FROM A MULTIPLE SOURCE ARRAY[a]

Emission species	Source severity[b]		
	Bituminous	Anthracite	Lignite
Particulates	1.1×10^{-1}	2.0×10^{-2}	4.1×10^{-1}
SO_x	5.3×10^{-1}	1.3×10^{-1}	5.0×10^{-1}
NO_x	1.9×10^{-1}	5.0×10^{-2}	2.4×10^{-1}
Hydrocarbons	1.3×10^{-1}	5.0×10^{-2}	3.0×10^{-2}
CO	2.0×10^{-3}	1.0×10^{-3}	2.0×10^{-4}
Polycyclic organic materials	9.1×10^{1}	1.7	
Polychlorinated biphenyls	$<2.0 \times 10^{-5}$		
Formaldehyde	5.0×10^{-4}		
Elements:			
Aluminum	2.5×10^{-1}	3.4×10^{-1}	9.0×10^{-2}
Antimony	2.0×10^{-3}	2.0×10^{-3}	1.0×10^{-3}
Arsenic	6.0×10^{-2}	2.0×10^{-2}	3.0×10^{-2}
Barium	3.0×10^{-2}	3.0×10^{-2}	1.9×10^{-1}
Beryllium	1.6×10^{-1}	1.7×10^{-1}	2.0×10^{-2}
Bismuth	2.0×10^{-6}	2.0×10^{-6}	
Boron	5.0×10^{-4}	2.0×10^{-4}	3.0×10^{-3}
Bromine	2.0×10^{-3}	2.0×10^{-3}	
Cadmium	2.0×10^{-2}	8.0×10^{-3}	4.0×10^{-3}
Calcium	4.0×10^{-2}	2.0×10^{-2}	5.8×10^{-1}
Chlorine	1.6×10^{-1}	3.7×10^{-1}	6.0×10^{-2}
Chromium	3.0×10^{-2}	3.0×10^{-2}	5.0×10^{-3}
Cobalt	1.0×10^{-2}	1.0×10^{-2}	2.0×10^{-3}
Copper	4.0×10^{-3}	5.0×10^{-3}	1.0×10^{-3}
Fluorine	6.0×10^{-2}	5.0×10^{-2}	3.0×10^{-2}
Gallium	8.0×10^{-4}	9.0×10^{-4}	2.0×10^{-4}
Iron	6.0×10^{-1}	1.5×10^{-1}	6.3×10^{-1}
Lead	1.2×10^{-1}	9.0×10^{-2}	4.0×10^{-2}
Lithium	4.0×10^{-4}	6.0×10^{-4}	5.0×10^{-6}
Magnesium	1.0×10^{-3}	1.0×10^{-3}	8.0×10^{-3}
Manganese	2.0×10^{-2}	7.0×10^{-4}	2.0×10^{-3}
Mercury	6.0×10^{-3}	7.0×10^{-3}	5.0×10^{-3}
Molybdenum	7.0×10^{-4}	5.0×10^{-4}	7.0×10^{-4}
Nickel	2.0×10^{-2}	3.0×10^{-2}	5.0×10^{-3}
Niobium	2.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
Phosphorus	1.0×10^{-2}	1.0×10^{-2}	8.0×10^{-2}
Potassium	1.8×10^{-1}	2.1×10^{-1}	2.0×10^{-2}
Scandium	8.0×10^{-5}	9.0×10^{-5}	2.0×10^{-5}
Selenium	3.0×10^{-2}	3.0×10^{-2}	7.0×10^{-3}
Silicon	4.2×10^{-1}	4.6×10^{-1}	2.1×10^{-1}
Silver	3.0×10^{-3}	2.5×10^{-1}	2.5×10^{-1}
Sodium	3.0×10^{-2}	4.0×10^{-2}	4.4×10^{-1}
Strontium	2.0×10^{-3}	2.0×10^{-3}	8.0×10^{-3}
Tellurium	3.0×10^{-3}	1.0×10^{-3}	
Thallium	1.0×10^{-3}	6.0×10^{-2}	
Thorium	4.0×10^{-3}	3.0×10^{-3}	5.0×10^{-3}
Tin	3.0×10^{-5}	2.0×10^{-5}	1.0×10^{-5}
Titanium	1.0×10^{-2}	3.0×10^{-2}	8.0×10^{-3}
Uranium	8.0×10^{-4}	2.0×10^{-3}	9.0×10^{-4}
Vanadium	6.0×10^{-3}	7.0×10^{-3}	2.0×10^{-3}
Ytterbium	8.0×10^{-5}	2.0×10^{-5}	5.0×10^{-6}
Yttrium	2.0×10^{-3}	2.0×10^{-3}	7.0×10^{-4}
Zinc	5.0×10^{-3}	4.0×10^{-3}	1.0×10^{-3}
Zirconium	2.0×10^{-3}	2.0×10^{-3}	5.0×10^{-4}

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[a] Blanks indicate data not available.

[b] Emissions assumed constant over a 24-hr period during the heating season.

The affected population is defined as the population living in the area around a representative source where $\overline{\chi}/F$ is greater than 0.05 or 1.0. The mathematical derivation of the affected population can be found in Appendix E. The affected population for coal-fired residential combustion emissions from a single source is presented in Table 32 and was determined from the population density for the average sources described in Section 3.

TABLE 32. AFFECTED POPULATION FOR SINGLE SOURCE EMISSIONS
(Number of persons)

	Bituminous		Anthracite		Lignite	
Emissions species[a]	$\overline{\chi}/F > 0.05$	$\overline{\chi}/F > 1.0$	$\overline{\chi}/F > 0.05$	$\overline{\chi}/F > 1.0$	$\overline{\chi}/F > 0.05$	$\overline{\chi}/F > 1.0$
Polycyclic organic materials	115	5	3	0	0	0

[a] Only species with affected populations greater than zero are listed.

Like source severity, the population affected by multiple residential coal combustion sources is much greater than that affected by a single source. Maximum ground-level concentrations of a specific pollutant will be higher for multiple sources. Consequently, the area of land and affected population covered by a ground-level concentration corresponding to a specified $\overline{\chi}/F$ is much greater for multiple sources.

Although the model for single source affected population cannot be applied to multiple sources, the affected population can be predicted from the concentration isopleth diagram (Figure 13) and the maximum ground-level concentration of each pollutant. The affected population is those persons who live in an area around the source where $\overline{\chi}/F$ is >1.0 or >0.05. Because F is known for a particular pollutant, $\overline{\chi}$, the average ground-level concentration, can be calculated for each condition of $\overline{\chi}/F$. But the isopleth diagram expresses ground-level concentrations in terms of percent of maximum ground-level concentration. Therefore, dividing $\overline{\chi}$ by χ_{max}, as determined from the calculation of severity for multiple sources, gives limits of the downwind distance where $\overline{\chi}/F$ >1.0 or >0.05 in terms of percent of maximum ground level concentration. These limits correspond to a distance in kilometers on the Y axis of the isopleth diagram and can be used to calculate x_1 and x_2, distance from the center of the housing array.

Several simplifying assumptions had to be made at this point:

1. The housing array was treated as a single source with the emission point in its center.

2. When x_1 fell within the array of houses, it was assigned the value corresponding to the outermost distance of the array.

3. The population density around the array of houses was chosen to be the average population density for standard metropolitan statistical areas, or 139 persons/km^2 (57).

With these assumption, x_1 and x_2 define the area of land around a housing array affected by ground level concentrations of a pollutant where $\overline{\chi}/F$ >1.0 and 0.05. The affected population can then be determined using the population density of 139 persons/km^2.

Table 33 presents the affected population for coal-fired residential combustion emissions generated by multiple sources. Because of assumption 2, described above, these numbers exclude the population of the housing array. Most of the housing array actually falls within the affected areas; therefore, the population of the array should also be considered. Assuming an average of 2.9 persons per household (57), 2,900 persons within the housing array would also be affected. Comparing this to Table 32, it can be seen that for many pollutants the population within the array is that most affected due to the low stack heights. For others, such as POM's, the area affected by the designated hazardous concentration extends beyond the bounds of this model corresponding to the 1% isopleth in Figure 13.

State and National Emission Burden

Another measure of the potential impact on the environment is the total annual emissions of each criteria pollutant. Estimated annual emissions from coal-fired residential combustion equipment on a state-by-state basis are derived and tabulated in Appendix F. These were calculated using emission factors and fuel usage estimates. The appendix also shows the percent contribution of each source type to the total state emission burden from all stationary sources.

The tables in Appendix D show that in 1974 residential combustion of bituminous coal had the greatest impact on emissions on a state-by-state basis, exceeding 1% of the total state SO_x emissions in the District of Columbia, Virginia, and West Virginia.

Total national criteria emissions from each source with corresponding national emission burdens are given in Table 34.

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(57) Statistical Abstracts of the United States 1975. U.S. Department of Commerce, Washington, D.C., July 1975. 1050 pp.

TABLE 33. POPULATION AFFECTED BY EMISSIONS FROM MULTIPLE SOURCES (Number of persons)

Emissions species[a]	Bituminous		Anthracite		Lignite	
	$\bar{\chi}/F > 0.05$	$\bar{\chi}/F > 1.0$	$\bar{\chi}/F > 0.05$	$\bar{\chi}/F > 1.0$	$\bar{\chi}/F > 0.05$	$\bar{\chi}/F > 1.0$
Particulate	585	0	0	0	3,826	0
SO_x	4,361	0	783	0	>5,000[b]	0
NO_x	1,593	0	0	0	2,403	0
HC	783	0	0	0	0	0
POM	>5,000[b]	>5,000[b]	>5,000[b]	352	0	0
Elements:						
Aluminum	2,537	0	3,326	0	394	0
Arsenic	99	0	0	0	0	0
Barium	0	0	0	0	1,560	0
Beryllium	1,174	0	1,218	0	0	0
Calcium	0	0	0	0	4,766	0
Chlorine	1,174	0	3,473	0	97	0
Fluorine	98	0	0	0	0	0
Iron	4,930	0	1,035	0	>5,000[b]	0
Lead	714	0	394	0	0	0
Magnesium	0	0	0	0	296	0
Phosphorus	0	0	0	0	296	0
Potassium	1,353	0	1,853	0	0	0
Silicon	3,826	0	3,852	0	1,853	0
Silver	0	0	2,537	0	2,537	0
Sodium	0	0	0	0	4,089	0
Thallium	0	0	98	0	0	0

[a] Only species with affected population greater than zero are listed.

[b] Actual number could not be determined because of the limits of the isopleth diagram in Figure 13.

TABLE 34. ESTIMATED ANNUAL CRITERIA EMISSIONS AND BURDEN FROM COAL-FIRED RESIDENTIAL COMBUSTION FOR 1974

Emission species	Total annual emissions, metric tons/yr			National emission burden, percent of total of all stationary sources		
	Bituminous	Anthracite	Lignite	Bituminous	Anthracite	Lignite
Particulate	14,425	937	244	0.08	<0.01	<0.01
SO_x	66,104	6,916	423	0.2	0.02	<0.01
NO_x	5,210	769	56	0.02	<0.01	<0.01
Hydrocarbons	5,376	1,110	9	0.02	<0.01	<0.01
CO	58,032	7,089	19	0.05	0.01	<0.01

A comparison of the national emissions of criteria pollutants from coal-fired residential combustion to other forms of residential combustion (Table 35) shows that coal combustion contributes between 2% and 30% of the total from the residential sector.

TABLE 35. TOTAL ANNUAL EMISSIONS OF CRITERIA POLLUTANTS FROM RESIDENTIAL COMBUSTION SOURCES[a]

	Emissions, metric tons/yr				
Fuel type	Particulates	SO_x	NO_x	Hydrocarbons	CO
Utility, bottled, tank or L.P. gas (2)	47,000	1,400	191,000	19,000	49,000
Fuel oil, kerosene, etc. (2)	74,000	1,090,000	89,000	23,000	37,000
Coal	15,606	73,443	6,035	6,495	65,140
Wood (2)	23,000	3,400	23,000	4,500	4,500

[a] Coal emissions were determined in this report; others are from Reference 2.

Annual national emissions of POM from automatic, coal-fired, residential combustion units are about 101 metric tons from bituminous coal-firing and 0.9 metric tons from anthracite coal-firing. A study conducted in 1967 estimated the total annual POM emissions from residential coal combustion to be about 372 metric tons or 85% of all POM emissions nationally (39). A more recent survey found these emissions to be 243 metric tons annually, but in this case, that represented only 3.4% of all POM emissions nationally. The survey showed that POM emissions from coal refuse piles account for 82% and those from coke manufacturing account for 9% of the national total POM emissions (58). The earlier study did not list coal refuse piles and considered POM emissions from coke manufacturing as negligible.

A study of coal refuse pile emissions presents a POM emission rate of about 1.3×10^{-8} kg/hr per metric ton of burning refuse and an estimated 250×10^{6} metric tons of refuse in 1968 (59). This yields a total annual POM emission that is about two orders of magnitude lower than that in the recent survey. At this rate, the annual POM emissions from residential coal combustion are about 10% of the national total. Although this number is uncertain, it does indicate that increased residential coal combustion may have a significant impact on POM emissions nationally and may have an even greater impact on state and local POM emission levels.

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(58) Eimutis, E. C., R. P. Quill, and G. M. Rinaldi. Source Assessment: Noncriteria Pollutant Emissions (1978 Update). EPA 600/2-78-004t, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July 1978. 149 pp.

(59) Chalekode, P. K., and T. R. Blackwood. Source Assessment: Coal Refuse Piles, Abandoned Mines and Outcrops, State-of-the-Art. EPA 600/2-78-004v, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July 1978. 51 pp.

SECTION 5

CONTROL TECHNOLOGY

Because of the past decline of coal-fired residential heating systems, there has been little interest in controlling emissions from these sources. No add-on emission control devices are currently on the market; however, any improvement in combustion efficiency will usually result in some improvement of emission levels. Two studies of emissions from coal-fired equipment in the residential size range have recently been completed (6, 15). Although no definite conclusions can be reached, the results indicate several possibilities. The condition of the fuel bed is important in reducing emissions, such as particulates and POM's, since a poor fuel bed can result in incomplete combustion. Fuel bed conditions can be improved by burning coals such as anthracite or western subbituminous coal which have low caking properties. Coals containing excessive fines can interefere with the uniform distribution of combustion air and contribute entrained particles to the flue gas.

Coal properties also affect emission levels. Burning a coal with low volatile content such as anthracite or low volatile bituminous will result in lower particulate and POM emissions than burning coals with high volatile content. Western coals with high lime content in the ash may have a smaller fraction of their sulfur content emitted due to reaction with the lime during combustion (6, 15, 22).

Experiments with overfire air during combustion indicate that visible emissions from coals with volatile contents of over 20% by weight are eliminated with overfire air. However, the visible emissions reduction did not significantly affect particulate emissions levels (6).

Concentrations of particulate, POM's, and carbon monoxide leaving the combustion chamber have been found to be highest from the OFF segment of the heating cycle during tests burning high volatile bituminous coal. It was observed that residential bituminous stokers operate at one speed with the combustion air fan and the feed screw running concurrently. This results in excessive amounts of air during the initial ON segment and a deficiency in combustion air during the initial OFF period (6, 15).

In the combustion of high volatile bituminous coals, modification of this cycle to achieve a better control of combustion air during these periods resulted in a reduction of POM and particulate emissions. The modification had no effect on emissions from the combustion of western subbituminous coal (6).

Processed smokeless coals were suggested (6) for reducing particulates and POM emissions. However, the one test that was conducted proved inconclusive, since the processed coal (lignite char) was soft and broke into fine particles, resulting in a high particulate loading.

In general, it was concluded that emissions from stoker-fired boilers can be reduced by providing overfire air and proper control of combustion (a modified cycle). In addition, proper choice of coals (anthracite, western subbituminous and processed coals) can reduce emissions (6). However, these coals are either in limited supply or are not located near the largest potential market.

One report proposed that all clean fuels such as low sulfur coal be allocated to the residential sector since add-on control technology would be financially impossible for most consumers (60). However, the problem of high coal transportation costs from the mine to the market area remains, because the cleaner coals are located far from the largest potential markets.

A study was performed to evaluate emission reduction techniques in oil- and gas-fired residential furnaces (61), which, in some areas, can apply to coal-fired units. Table 36 summarizes those control strategies that may apply to coal-fired equipment. A major problem of burning coal in the residential sector is the caking properties of bituminous coals (6). One research effort demonstrated that the caking properties of coal (free swelling index) can be destroyed by reacting the coal with boron trifluoride (62). Table 37 shows the results of this study and indicates

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(60) Hall, E. H., P. S. K. Choi, and E. L. Kropp. Assessment of the Potential of Clean Fuels and Energy Technology. EPA 600/2-74-001 (PB 239 970), U.S. Environmental Protection Agency, Washington, D.C., February 1974. 193 pp.

(61) Brown, R. A., C. B. Moyer, and R. J. Schreiber. Feasibility of a Heat and Emission Loss Prevention System for Area Source Furnaces. EPA-600/2-76-097 (PB 253 945), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, April 1976. 187 pp.

(62) Chakrabartty, S. K., and N. Berkowitz. Properties of Caking Coals: Destruction of Caking Properties by Boron Trifluoride. Fuel, 51(1):44-46, 1972.

TABLE 36. COMBUSTION CONTROL STRATEGIES FOR REDUCING AIR POLLUTANTS FROM RESIDENTIAL HEATING EQUIPMENT (61)

Control strategy	Impacted pollutant emission	Comments
Excess air level	NO_x	As excess air is increased, CO, HC, and smoke pass through a minimum, but NO_x passes through a maximum Optimum pollutant and thermal efficiency level occurs at a stoichiometric ratio greater than one
Combustion chamber design	NO_x CO Hydrocarbons Smoke/particulate	Combustion chamber design affording long residence time at high temperature minimizes smoke, particulates, CO, HC, but may increase NO_x Refractory-lined chamber affords better combustion and lower emissions
Service and maintenance	NO_x CO Hydrocarbons Smoke/particulate	Equipment state-of-repair very important for providing breadth for reducing emissions by other methods Air filter should be replaced regularly

TABLE 37. EFFECT OF BORON TRIFLUORIDE ON FREE SWELLING INDEX AND VOLATILE MATTER OF HIGH VOLATILE BITUMINOUS COALS (62)

			Nitrogen/boron trifluoride at temperature shown					
Coal	Parameter	Initial	25°C	50°C	100°C	150°C	200°C	250°C
No. 1	Free swelling index	6.5	0	0	0	0	0	0
	Percent volatile matter, by wt	30.6	26.5	26.8	27.2	27.2	26.7	27.7
No. 2	Free swelling index	4	1.5	1	1	1	0.5	0
	Percent volatile matter, by wt	29.1						26.1

Note.—Blanks indicate no data reported in reference cited.

that caking properties can be destroyed at temperatures as low as 25°C without significant change in volatile content. The cost of this process was not discussed, and therefore its viability in the residential coal market is unknown.

Emissions studies have not been conducted with this coal and it is not known what effect the boron trifluoride will have on other emissions or on equipment corrosion.

SECTION 6

GROWTH AND NATURE OF THE SOURCE

Before the twentieth century, coal and wood were the predominant fuels available for residential heating in the United States. Near the turn of the century gas and oil entered the home heating market. However, these fuels were only available to a small number of homes near the source. Developments around 1920 made it possible to deliver large quantities of these fuels to distant markets and signaled the decline of coal and wood use for home heating. Coal was still a major home heating fuel in 1940, when 19,000,000 occupied housing units burned it for primary heating purposes (57). This was about 54% of the total number of occupied housing units in the United States. From that point, however, the decline was rapid. By 1970, housing units burning coal for heat numbered about 1,800,000 units (5), accounting for less than 3% of the total number of occupied housing units. By 1974, coal-fired heating declined to 740,000 housing units, a 60% drop from 1970 (1). Figure 15 shows the decline of coal-fired residential heating.

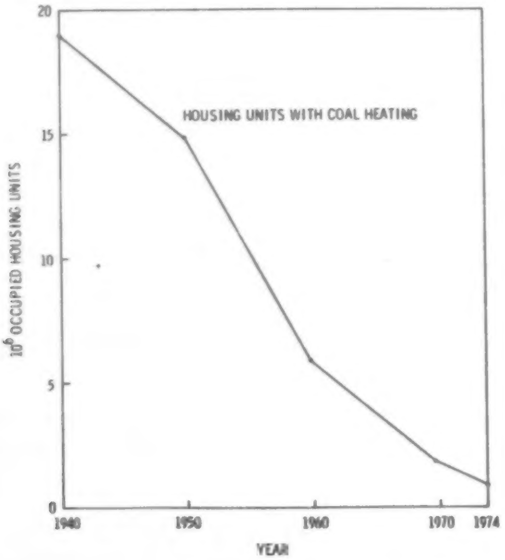

Figure 15. Residential coal-firing heating trends (57).

Most recent figures on the population of coal-fired heating devices are not available. However, most manufacturers agree that there is increased interest in this type of home heating, although not all manufacturers are seeing a corresponding increase in sales (18, 63, 64).

In spite of high heating bills, most people are not willing to rely on coal for heat. Statistics on the shipments of solid fuel heating equipment indicate a sudden demand for stove type heating devices, starting around 1973. In 1972, total solid fuel residential heating equipment shipped was about 229,000 units (65). In 1975, the number jumped to about 605,000 units. Of these, 254 were stokers, and 2,233 were forced-air furnaces. The remainder were domestic heating stoves (66, 67). Stokers have not yet increased in sales, but sales of warm-air furnaces increased 450% from 1972 to 1976 (65-68). Approximately 75% of the heating stoves shipped in 1976 were classified as coal and wood burners. Figure 16 shows the trends in shipments of solid fuel residential heating devices (65-76). Modern coal-fired warm-air furnaces are designed to be more appealing to today's homeowners. Sales have been limited to the West, because these units are designed to burn subbituminous coal most effectively. One manufacturer claims that a large potential market exists in the East for coal-fired warm-air furnaces capable of burning bituminous coal (63).

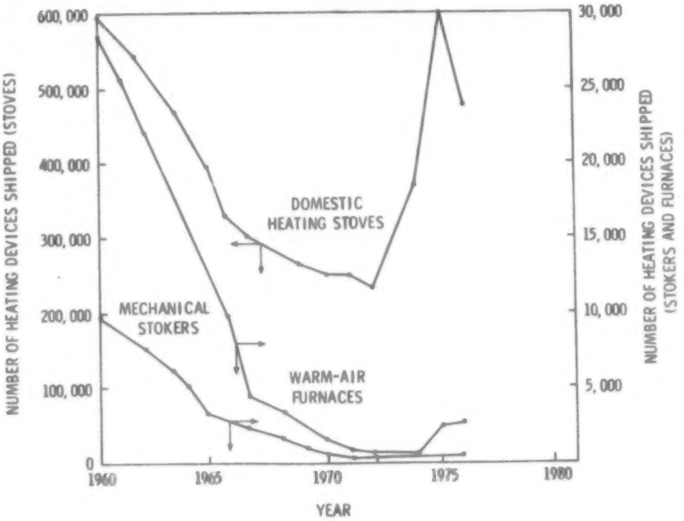

Figure 16. Shipments of coal- and wood-fired residential heating devices (65-76)

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(63) Personal communication with B. Prill, Prill Manufacturing Corporation, Sheridan, Wyoming, 7 December 1976.

(64) Personal communication with James E. Axeman, Axeman - Anderson Company, Williamsport, Pennsylvania, 6 October 1977.

(continued)

There are conflicting opinions as to whether residential coal combustion is on the increase and, if so, whether the increase will be significant enough to cause environmental problems. Part of the conflict may be the result of regional trends. Recently released estimates of housing units heating with coal in 1975 showed a 50% increase in the West while the remainder of the country exhibited a 25% decline (77). The interest in coal heating is so strong in Colorado that contractors are building homes with the option of coal heating. As a result, the Colorado Department of Health was forced to institute a permit program for residential coal heating devices (78).

(continued)

(65) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, MA-34N(72)-1, U.S. Department of Commerce, Washington, D.C., November 1973. 9 pp.

(66) Current Industrial Reports, Selected Heating Equipment. Bureau of the Census, MA-34N(75)-1, U.S. Department of Commerce, Washington, D.C., July 1976. 6 pp.

(67) Current Industrial Reports, Air Conditioning and Refrigeration Equipment Including Warm Air Furnaces. Bureau of the Census, MA-35M975)-1, U.S. Department of Commerce, Washington, D.C., October 1976. 14 pp.

(68) Current Industrial Reports, Air Conditioning and Refrigeration Equipment Including Warm Air Furnaces. Bureau of the Census, MA-35M(76)-1, U.S. Department of Commerce, Washington, D.C., July 1977. 14 pp.

(69) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, M34N(60)-13, U.S. Department of Commerce, Washington, D.C., August 1961. 7 pp.

(70) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, M34N(64)-13, U.S. Department of Commerce, Washington, D.C., July 1966. 9 pp.

(71) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, M34N(65)-13, U.S. Department of Commerce, Washington, D.C., January 1967. 9 pp.

(72) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, M34N(66)-13, U.S. Department of Commerce, Washington, D.C., February 1968. 9 pp.

(73) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, M34N(67)-13, U.S. Department of Commerce, Washington, D.C., January 1969. 7 pp.

(74) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, M34N(69)-13, U.S. Department of Commerce, Washington, D.C., February 1971. 7 pp.

(continued)

A recent study on the feasibility of introducing coal into the residential sector led to the following conclusions related to its potential growth (55):

1. Direct use of coal in cities and large residential areas will result in severe environmental problems.
2. Emissions of particulates, SO_2, NO_x, hydrocarbons, and CO will be much greater from coal-fired residential combustion than from gas- or oil-fired furnaces.
3. Significant social and institutional problems will need to be overcome.
4. People will resist the inconvenience of handling and storing coal, and ash disposal.
5. Problems will be encountered in reestablishing a retail coal distribution system, especially without the existence of an established market.
6. On a total cost basis, the economics of increased residential coal combustion appears to be generally unfavorable.
7. Renewed interest in coal-fired furnaces in the Mountain and the West North Central regions is likely to have little impact on the total energy demand in the residential sector.

Although national trends remain difficult to predict, it is obvious that coal heating is increasing in certain parts of the country. The future of coal heating will depend on equipment and fuel availability, comparative costs of other fuels, and the impact of governmental emission regulations.

(continued)

(75) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, M34N(70)-13, U.S. Department of Commerce, Washington, D.C., December 1971. 9 pp.

(76) Current Industrial Reports, Selected Heating Equipment. Bureau of the Census, MA34N(76)-1, U.S. Department of Commerce, Washington, D.C., August 1977. 7 pp.

(77) Current Housing Reports, Bureau of the Census Final Report H-150-75; Annual Housing Survey: 1975, Part A; General Housing Characteristics for the United States and Regions. U.S. Department of Commerce, Washington, D.C., April 1977. 270 pp.

(78) Personal communication with J. Scott Kinsey, Colorado Department of Health, Denver, Colorado, 14 March 1977.

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APPENDIX A

DETERMINATION OF REPRESENTATIVE SOURCES

FUEL FEED RATE DETERMINATION FOR A REPRESENTATIVE SOURCE

Because a representative source is defined by average conditions, the fuel feed rate of the source is based on the average heat load of each source. This average heat load is computed by weighting the average number of heating degree-days of each state (60) where the source is located by the number of housing units burning that fuel in each state. Therefore,

Weighted average of heating degree-days for a source

$$= \sum_{i=1}^{50} \frac{(\text{Degree-days})_i (\text{housing units burning coal type})_i}{\text{U.S. total housing units burning coal type}} \qquad \text{(A-1)}$$

where i = each state

Table A-1 lists the average heating degree-days for each state for a 30-year period from 1941 to 1970.

Annual fuel usage is then determined by the amount of fuel needed per degree-day per dwelling unit which Reference 34 gives as 1.1 kg/degree-day per dwelling unit for coal. Assuming that the bulk of the heating season for bituminous and anthracite coal is about 212 days (October 1 to April 30) and that for lignite combustion in North Dakota is 243 days (September 15 to May 15), the average hourly feed rate of a representative combustion unit can be determined. For residential combustion of bituminous, anthracite, and lignite coals the average hourly feed rates were determined to be 1.1 kg/hr, 1.2 kg/hr, and 1.7 kg/hr, respectively.

DETERMINATION OF REPRESENTATIVE SOURCE EMISSION HEIGHT

Emission heights of residential combustion equipment will vary with building height and placement within a buidling. The minimum recommended chimney height for coal-fired residential units is 10.7 m above the stoker feet, 6.1 m to 7.6 m above the boiler for stoker-fired units, and 8.5 m to 9.8 m above the boiler for

TABLE A-1. ANNUAL HEATING DEGREE-DAYS AND HOUSING UNITS BURNING COAL FOR ALL STATES

State	Degree days[b]	Number of housing units in 1974[a]		
		Bituminous	Anthracite	Lignite
Alabama	1,684	20,384	0	0
Alaska	9,007	779	0	0
Arizona	1,552	92	0	0
Arkansas	3,354	971	0	0
California	2,331	286	0	0
Colorado	6,016	3,427	0	0
Connecticut	6,350	0	776	0
Delaware	4,940	0	645	0
Dist. Columbia	4,211	3,333	461	0
Florida	767	183	0	0
Georgia	3,095	9,412	0	0
Hawaii	0	34	0	0
Idaho	5,833	5,114	0	0
Illinois	6,113	28,889	595	0
Indiana	5,577	4,771	1,165	0
Iowa	6,710	1,421	0	0
Kansas	4,687	174	0	0
Kentucky	4,640	51,321	0	0
Louisiana	1,465	22	0	0
Maine	7,498	0	795	0
Maryland	4,729	0	8,131	0
Massachusetts	5,621	575	1,976	0
Michigan	7,086	4,773	1,637	0
Minnesota	9,034	1,782	0	0
Mississippi	2,300	2,002	0	0
Missouri	4,956	1,406	0	0
Montana	7,652	1,125	0	0
Nebraska	6,049	272	0	0
Nevada	6,022	175	0	0
New Hampshire	7,360	0	461	0
New Jersey	4,946	0	10,211	0
New Mexico	4,292	248	0	0
New York	6,221	357	28,391	0
North Carolina	3,366	18,207	0	0
North Dakota	9,044	0	0	1,028
Ohio	5,642	9,923	1,074	0
Oklahoma	3,695	165	0	0
Oregon	4,792	613	0	0
Pennsylvania	5,398	40,625	103,742	0
Rhode Island	5,972	0	137	0
South Carolina	2,598	8,842	0	0
South Dakota	7,838	309	0	0
Tennessee	3,462	47,885	0	0
Texas	2,134	134	0	0
Utah	5,983	4,464	0	0
Vermont	7,876	0	768	0
Virginia	3,714	35,426	0	0
Washington	6,010	2,991	0	0
West Virginia	4,590	29,926	0	0
Wisconsin	7,444	3,227	0	0
Wyoming	7,255	875	0	0
Total	-[c]	346,940	160,965	1,028

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[a] Values are derived in Appendix B from data in References 1 and 31.

[b] Data in Reference 57 are given for major cities in each state. For this study, it was assumed that these numbers approximated state averages.

[c] Not applicable.

hand-fired units (9, 79). Assuming all units are located in a basement approximately 3 m below ground level, the emission height is taken to be 6.1 m above ground.

AVERAGE POPULATION DENSITY OF A REPRESENTATIVE SOURCE

To determine the affected population for a pollutant from an emission source, the population density around the source must be known. For sources such as coal-fired residential combustion equipment, the associated population density can best be represented by a weighted average population density for each state where that source is located. This can be represented by the expression:

Weighted average population density for all states

$$= \sum_{i=1}^{50} \frac{(\text{Population density})_i (\text{housing units burning coal type})_i}{\text{U.S. total housing units burning coal type}} \qquad \text{(A-2)}$$

where i = each state

Table A-2 lists the population densities for each state for 1974.

In the case of lignite combustion, a weighted average was not needed because it is assumed all lignite-fired residential combustion takes place in North Dakota.

DETERMINATION OF A TYPICAL BURNING CYCLE FOR AUTOMATIC COAL-FIRED EQUIPMENT

The typical burning cycle represents the operation of an automatic coal-fired residential heating system located in an area and at a time of year with an average heat demand. Using Equation A-1 for all coal gives a weighted average heat load of 4,809 degree-days.

Assuming that the typical residential housing unit has a furnace of about 105-MJ/hr output operated at about 75% load and burning a coal with 26.7-MJ/kg heating value, the furnace feed rate can be calculated as follows:

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(79) Technical Manual on Industry Standards, Recommended Practices and Technical Information, Second Edition. Stoker Manufacturers' Association, Chicago, Illinois, 1947.

TABLE A-2. STATE POPULATION DENSITIES FOR 1974 (57)

State	Population density, persons/km^2	State	Population density, persons/km^2
Alabama	27	Montana	1.9
Alaska	0.2	Nebraska	7.7
Arizona	7.3	Nevada	2.0
Arkansas	15	New Hampshire	35
California	52	New Jersey	376
Colorado	4.3	New Mexico	3.6
Connecticut	245	New York	146
Delaware	112	North Carolina	42
Dist. Columbia	4,575	North Dakota	3.6
Florida	58	Ohio	101
Georgia	32	Oklahoma	15
Hawaii	51	Oregon	9.3
Idaho	3.7	Pennsylvania	102
Illinois	77	Rhode Island	345
Indiana	57	South Carolina	36
Iowa	20	South Dakota	3.5
Kansas	11	Tennessee	39
Kentucky	33	Texas	18
Louisiana	32	Utah	5.4
Maine	13	Vermont	20
Maryland	160	Virginia	47
Massachusetts	286	Washington	20
Michigan	62	West Virginia	29
Minnesota	19	Wisconsin	32
Mississippi	19	Wyoming	1.4
Missouri	27		

$$\frac{105\ \text{MJ/hr} \times 0.75}{26.7\ \text{MJ/kg}} = 2.9\ \text{kg/hr}$$

To determine the length of time the furnace must operate, the following calculation is performed:

$$4{,}809\ \text{degree-days/yr} \times 1.1\ \text{kg coal/degree-day per dwelling unit} \cong 5{,}290\ \text{kg/yr of coal}$$

Assume a heating season of 212 days; therefore

$$5{,}290\ \text{kg/yr} \div 212\ \text{days} = 25\ \text{kg/day}$$

Furthermore,

$$25\ \text{kg/day} \div 2.9\ \text{kg/hr} = 8.6\ \text{hr/day}$$

$$\frac{8.6 \text{ hr/day} \times 60 \text{ min/hr}}{24 \text{ hr/day}} = 22 \text{ min/hr}$$

when combustion takes place, while for 38 min/hr the fuel bed is inactive.

APPENDIX B

ESTIMATION OF THE SOURCE POPULATION AND FUEL CONSUMPTION

The most recent published data on the population of coal-fired heating equipment are in the 1974 Annual Housing Survey published by the U.S. Bureau of Census. However, this report is based on data collected from a sample population; it lacks the detail necessary to adequately characterize the whole population. The 1970 Census of Housing surveyed the total population and is much more detailed than the 1974 Housing Survey. To obtain a better estimate of the 1974 population this appendix employs certain relationships and trends observed in various tables from both surveys.

Table B-1 is from the 1970 Census of Housing and shows the number of housing units burning coal for heat by type of heating equipment. The population of heating equipment cannot be directly inferred from this table, however, and to determine the population of primary coal-fired heating equipment, the following assumptions are made:

1. Single-unit structures (including mobile homes and trailers) have one primary heating device.
2. All owner-occupied multiunit structures heating with coal combustion do not exceed two housing units per structure.
3. Multiunit structures have one primary heating device per structure;
   - for two-unit structures, the number of housing units is divided by two to estimate the average number of heating devices;
   - for three- and four-unit structures (assuming a normal distribution), the number of housing units is divided by 3.5 to estimate the average number of heating devices;
   - for 5- to 19-unit structures (assuming a normal distribution), the number of housing units is divided by 12 to estimate the average number of heating devices; and

TABLE B-1. POPULATION OF HOUSING UNITS BURNING COAL FOR HEAT (5)

	Housing units, 1970									
	Owner occupied			Renter occupied						
Heating equipment	1-unit structures	2 units or more per structure	Mobile home or trailer	1-unit structures	2-unit structures	3 & 4 units per structure	5 to 19 units per structure	20 units or more per structure	Mobile home or trailer	Total
Steam or hot water	148,783	34,374	136	38,976	33,406	43,621	148,569	143,135	114	591,114
Warm-air furnace	404,304	22,592	1,234	102,571	24,274	10,896	10,488	6,897	392	583,648
Floor, wall, or pipeless furnace	38,682	1,619	336	13,359	2,605	1,223	1,775	1,638	44	61,281
Other[a]	312,969	6,246	1,284	233,906	18,588	6,802	3,687	916	511	584,909
Total	904,738	64,831	2,990	388,812	78,873	62,542	164,519	152,586	1,061	1,820,952

[a] Fireplaces, stoves, or portable heaters.

- for 20 units or more per structure, the number of housing units is divided by 20 to estimate the upper limit of heating equipment for this size structure.

These assumptions transform Table B-1 into Table B-2.

TABLE B-2. POPULATION OF COAL-FIRED HEATING EQUIPMENT

Heating equipment	Estimated number of primary heating devices by structure size, 1970					
	1-unit[a] structures	2-unit structures	3 & 4-unit structures	5 to 19-unit structures	20 or more units per structure	Total
Steam or hot water	188,009	33,890	12,463	12,381	7,157	253,900
Warm-air furnace	508,501	24,433	3,113	874	345	536,266
Floor, wall, or pipeless furnace	52,421	2,113	349	148	82	55,113
Other[b]	598,670	12,417	1,943	307	46	563,383
Total	1,297,601	71,853	17,868	13,710	7,630	1,408,662

[a] Includes mobile homes and trailers.

[b] Fireplaces, stoves, or portable heaters.

Dividing the total number of heating devices by the total number of housing units establishes the following relationship for use on the 1974 data:

- 0.774 coal-fired heating device per housing unit heated by coal.
- 0.752 coal-fired heating device in one- and two-unit structures per housing unit heated with coal.

The 1970 Census of Housing also presents a state-by-state listing of housing units heated by coal. The 1974 survey does not give a state-by-state listing; instead it presents the housing units by region for 1970 and 1974. From this the percent change was computed for each region (Table B-3).

The regional percent change in housing units was applied to the respective states in the 1970 Census to estimate the 1974 state population of housing units burning coal. The previously established relationships of heating devices to housing units were then applied to these estimates to predict the state population of heating devices.

The amount and type of coal burned in the residential sector for each state has been estimated based on the 1970 Census of Housing, heat demand, and retail coal sales data (32). Dividing the total fuel usage by the number of housing units from the 1970 census

TABLE B-3. REGIONAL DISTRIBUTION OF HOUSING UNITS HEATING WITH COAL - 1970 and 1974 (1)

Year	Housing units Northeast	North central	South	West
1970	540,702	574,810	624,005	81,435
1974	244,000	165,000	306,000	26,000
	Percent change			
	-55	-86	-51	-68

gives an estimate of the amount of fuel burned per housing unit in each state. This number applied to the 1974 estimate of housing units burning coal provides a state-by-state estimate of fuel usage for 1974. The fuel usage presented in Reference 32 is for bituminous and anthracite coal. The ratio of bituminous coal to anthracite coal used in each state for residential heating is assumed to be the same as the ratio of bituminous coal-fired equipment to anthracite-fired equipment, establishing the population and distribution of these devices.

APPENDIX C

DERIVATION OF EMISSION FACTORS

Some calculations in this appendix have been made using nonmetric units; however, all final emission factors were converted to metric form in this appendix and in the text.

Source test measurements summarized in Tables C-1 through C-7 were used to derive average emission factors as described below.

BITUMINOUS COAL COMBUSTION

Five sources of information were employed to determine emission factors for residential combustion of bituminous coal. The most extensive testing was performed as a special project under this contract. The results of the special project (15) and another study (30) were presented in nonmetric units and were converted to metric for this report.

Emissions data on particulate, CO, hydrocarbons, NO_2, SO_2, and formaldehyde as lb/ton of coal (38) were merely converted to metric units. For emissions data on POM's as micrograms per 10^6 Btu heat input (38, 39), the heat input to the system and the fuel feed rate were used to calculate emission factors, as in the following example:

$$\frac{1{,}493{,}100\ \mu g}{10^6\ \text{Btu}} \times \frac{g}{10^6\ \mu g} \times \frac{58{,}000\ \text{Btu}}{\text{hr}} \times \frac{\text{hr}}{4.2\ \text{lb}} \times \frac{\text{lb}}{0.454\ \text{kg}}$$

$$= 0.045\ \text{g of POM/kg coal}$$

Data were also provided (6) for the emission of particulates, POM, SO_2, NO, and CO from residential combustion of bituminous coal. Particulate and POM emissions, presented in grams per pound and milligrams per pound respectively, can readily be converted to grams per kilogram. However, SO_2, NO, and CO emissions were presented as concentrations in the flue gas and listed separately for the ON and OFF portions of the furnace cycle. The stack gas volumes were not reported, but the amount of air, in pounds, fed to the combustion chamber during the ON portion of the cycle was presented. To determine the stack gas volume during the OFF portion of the cycle, it was necessary to back-calculate from the particulate emission factor and particulate loading for each test run.

TABLE C-1. EMISSION FACTORS FOR POM AND CRITERIA POLLUTANTS FROM COAL-FIRED RESIDENTIAL HEATING EQUIPMENT OPERATED ON A 20-MIN "ON"/40-MIN "OFF" HEATING CYCLE[a]

		Coal				Emission factor, lb/ton (lb/10^6 Btu)					
Test run number	Heating equipment[b]	Designation	Ash content,[c] %	Sulfur content,[c] %	Excess air, %	Particulates[d]	SO_x[e]	NO_x[f]	CO[g]	Condensable organics[h]	POM[i]
1,2	Boiler	A	10.9	0.41	238	5.0 (0.22)	6.0[j] (0.26)	12.8[j] (0.56)	0.26 (0.011)	2.0 (0.087)	0.26 (0.011)
3,4	Boiler	A	7.5	0.38	123	7.8 (0.33)	11.0[j] (0.46)	7.0[j] (0.29)	4.0 (0.17)	2.4 (0.10)	–[k]
5,6	Boiler	A	4.3	0.42	171	6.8 (0.28)	9.6[j] (0.39)	7.6[j] (0.31)	0.30 (0.012)	2.2 (0.089)	0.58 (0.023)
7,8	Boiler	B	9.1	1.5	128	2.8 (0.13)	17.8[j] (0.84)	2.8[j] (0.13)	0.08 (0.0038)	2.4 (0.11)	–[k]
9,10	Boiler	B	7.1	1.0	151	4.8 (0.22)	30[j] (1.4)	4.6[j] (0.21)	0.08 (0.0036)	3.6 (0.16)	–[k]
11,12	Boiler	B	5.0	0.58	160	5.8 (0.25)	14[j] (0.60)	6.4 (0.28)	0.08 (0.0035)	5.0 (0.22)	–[k]
13,14,15,16	Furnace	B	5.0	0.58	129	44 (1.9)	12.6 (0.54)	13.6 (0.59)	24 (1.0)	–[k]	0.070 (0.0030)
25,26,27,28	Furnace	B	7.1	1.0	–[k]	20 (0.90)	30 (1.4)	13.2 (0.60)	8.8 (0.40)	9.4 (0.42)	–[k]
17,18,19,20	Furnace	B	9.1	1.5	117	26 (1.2)	28 (1.3)	7.8 (0.37)	26 (1.2)	5.2 (0.25)	–[k]
21,22,23,24	Furnace	B	9.1	1.5	182	34 (1.6)	30 (1.4)	6.0 (0.28)	26 (1.2)	–[k]	0.036 (0.0017)
29	Furnace	C	3.3	0.47	207	4.0 (0.21)	–[k]	–[k]	–[k]	3.6 (0.19)	–[k]

[a] Most emission factors represent the average of duplicate sampling runs.

[b] Both units are rated at about 200,000 Btu/hr; boiler fuel feed rate averaged 19.8 lb/hr when stoker was ON, furnace fuel feed rate averaged 15.5 lb/hr when stoker was ON.

[c] As received. [d] Front half Method 5. [e] Method 6. [f] Method 7. [g] Dräger tube. [h] Back half Method 5. [i] Modified Method 5 with XAD-2 resin trap.

[j] Data for ON segment of heating cycle only. [k] No data obtained due to program limitations.

TABLE C-2. EMISSIONS DATA FOR BITUMINOUS COAL COMBUSTION[a] (6)

Run	Coal	Cycle ON/OFF min	Time segment[b]	Firing rate,[c] lb/hr	Air flow rate, lb/hr Prim.	Air flow rate, lb/hr Sec.	O_2, percent	CO_2, percent	SO_2, ppm	NO, ppm	CO, ppm	Particulate loading, mg/Nm³ ON cycle	Particulate loading, mg/Nm³ OFF cycle	POM loading, mg/Nm³ ON cycle	POM loading, mg/Nm³ OFF cycle	Particulate emissions, g/lb coal feed	POM emissions, mg/lb coal feed
1	High volatile bituminous	20/40	1 & 2	42	500	50	4.6 to 11.6	8.5 to 14.6	600 to 800	160 to 200	165 to >1,250	110	1,600	8.2	13	3.9	86
			3 & 4	0	0	0	13.9 to 15.8	4.6 to 6.0	360 to 420	55 to 60	>1,250						
2	High volatile bituminous	20/40	1 & 2	44	500	50	5.4 to 8.5	11.6 to 14.3	510 to 750	200 to 240	60 to 100	190	1,400	8.81	21	4.1	82
			3 & 4	0	0	0	17.0 to 18.5	2.4 to 3.6	150 to 180	30 to 40	>1,250						
3	High volatile bituminous	50/10[d]	1 & 2	44		50	5.0 to 6.5	15.2 to 16.5	630 to 900	600 to 900	40 to 100	100	1,300	3.2	29	0.85	23
			3 & 4	0	0	0	10.5 to 12.8	8.0 to 9.8	500 to 580	60 to 100	>1,250						
4	Western	20/40	1 & 2	55	640	60	10.5 to 12.3	8.1 to 9.8	210 to 270	120 to 130	560 to 850	50	99	1.2	1.5	0.50	10.2
			3 & 4	0	0	0	18.3 to 18.5	2.4 to 2.6	30 to 40	<40	>1,250						
6	Low volatile	20/40	1 & 2	52	610	60	5.5 to 12.0	8.0 to 16.0		120 to 170	<60	140	260	1.0	12	1.4	27
			3 & 4	0	0	0	11.0 to 15.8	4.6 to 9.0		30 to 50	>1,250						
7	Western	20/40	1 & 2	52	660	53	10.7 to 12.4	8.4 to 10.0			40 to 80	37	99			0.43	
			3 & 4	0	0	0	15 to 18	1.8 to 2.2			>1,250						
8	High volatile	20/40	1 & 2	43	500	50	7 to 10	9.4 to 11			40 to 160	110	590[e]				
			3 & 4	0	0	0	12 to 15	4.1 to 6.7			>1,250						
11	Western	20/40	1 & 2	23	350	0	12.5 to 15.5	2.0 to 7.0	120 to 180	80 to 100	150 to >1,250	45	61	0.53	0.22	1.0	8.3
			3 & 4	0	0	0	14.5 to 18.3	1.9 to 3.0	510 to 100	10 to 30	>1,250						
12	High volatile bituminous	20/40	1 & 2	75	760	75	4 to 6	13.0 to 13.8		200 to 250	40 to 80	120	610	0.81	0.33	2.1	8.8
			3 & 4	0	0	0	14 to 15	4.2 to 5.6		40 to 70	>1,250						
13	High volatile bituminous	20/40	1 & 2	23	350	40	10 to 13	6.5 to 7.9		120 to 170	>1,250	130	190	0.26	0.18	3.4	5.4
			3 & 4	0	0	0	15 to 17	3.5 to 4.5		40 to 70	>1,250						
14	Western	20/40	1 & 2	23	400	40	12 to 14	6.3 to 9.0		100 to 130	100 to 140	50	94	0.44	0.17	0.77	7.3
			3 & 4	0	0	0	16 to 18	2 to 4		40 to 60	>1,250						
15	Western	20/40	1 & 2	75	880	85	5 to 7	13.4 to 14.8	280 to 500	150 to 190	20 to 40	77	160	0.23	0.60	1.0	3.4
			3 & 4	0	0	0	14 to 18	2 to 5	80 to 100	25 to 50	>1,250						
16	Western	20/40[f]	1 & 2	50	600	60	9.5 to 12.8	7.1 to 10.2	190 to 240	100 to 140	50 to 150	37	87	0.98	0.58	0.60	11.1
			3 & 4	0	0	100	15.5 to 18.2	1.9 to 5.2	40 to 90	40 to 90	>1,250						
17	High volatile bituminous	20/40[f]	1 & 2	45	550	60	9.5 to 11.0	7.6 to 9.6		220 to 280	100 to 200	93	290	1.7	1.9	1.7	12.3
			3 & 4	0	0	100	15.0 to 17.5	2.6 to 3.8		50 to 80	>1,250						

Note.—Blanks indicate data not available.

[a] Data shown for runs 1 through 6 were combined by MRC to include transient and steady-state ON time segments.

[b] 1 - transient ON, 2 - steady-state ON, 3 - transient OFF, 4 - steady-state OFF.

[c] While ON.

[d] Did not use data because of 50/10 cycle; use all data from 20/40 cycle.

[e] Broken frit, run not used.

[f] Modified cycle, run not used.

TABLE C-3. POLYCYCLIC ORGANIC MATERIALS EMISSIONS DATA FOR BITUMINOUS COAL COMBUSTION (38)

(micrograms per million Btu heat input)

		Group 1							Group 2			
Source number in (38)	Firing method	Benzo(a)-pyrene	Pyrene	Benzo(e)-pyrene	Perylene	Benzo(g,h,i)-perylene	Anthan-threne	Cornene	Anthra-cene	Phenan-threne	Fluoran-thene	Benz(a)-anthra-cene
7	Underfeed stokers	3,800	7,700	5,400		580		1,200		29,000	47,000	560
8	Hand-stoked	400,000	600,000	100,000	60,000	300,000	90,000	30,000	400,000	1,000,000	1,000,000	

Note.—Blanks indicate data not available.

TABLE C-4. POLYCYCLIC ORGANIC MATERIALS EMISSIONS DATA FOR BITUMINOUS COMBUSTION (39)

(micrograms per million Btu heat input)

				Group 1							Group 2		
Sample number in (39)	Firing method	Fuel feed rate, lb/hr	Gross heat input, Btu/hr	Benzo(a)-pyrene	Pyrene	Benzo(e)-pyrene	Perylene	Benzo(g,g,i)-perylene	Anthan-threne	Cornene	Anthra-cene	Phenan-threne	Fluoran-threne
34	Underfeed stokers	4.2	58,000	65,000	300,000	39,000	7,900	61,000	6,100	4,100	70,000	610,000	330,000
36		3.8	56,000	81,000	190,000	59,000	4,800	58,000	3,000		48,000	350,000	150,000
59		5.0	70,000	67,000	160,000	55,000	5,500	59,000	1,300	3,400	14,000	170,000	320,000
60		4.5	63,000	8,600	45,000	7,700	430	6,300			1,300	51,000	76,000
57	Hand-stoked	6.3	89,000	1,700,000	2,700,000	870,000	220,000	1,400,000	270,000	49,000	1,100,000	2,300,000	4,300,000
58		5.6	80,000	3,300,000	9,100,000	1,500,000	350,000	2,200,000	490,000	97,000	2,900,000	7,500,000	11,000,000

Note.—Blanks indicate data not available.

TABLE C-5. EMISSION DATA FOR BITUMINOUS COAL COMBUSTION (38)

Source number in (38)	Firing method	Fuel feed rate, lb/hr	Gross heat input, Btu/hr	Total particulates, lb/ton of fuel	CO, lb/ton of fuel	Hydrocarbons (as methane), lb/ton of fuel	NO_x (as NO_2), lb/ton of fuel	SO_x (as SO_2), lb/ton of fuel	Formaldehyde, lb/ton of fuel
7	Underfeed stoker	4.8	66,000	12	1.1	3.3	9.8	32	
8	Hand-stoked	8	115,000	37	3.5	21	3.2	15	24×10^{-4}

Note.—Blanks indicate data not available.

TABLE C-6. EMISSIONS DATA FOR BITUMINOUS COAL COMBUSTION IN A RESIDENTIAL FIREPLACE FROM RUN NO. 13, STABLE CONDITIONS (30)

Burning rate, kg/hr	Stack gas flow rate, Nm^3/min	Particulate emission factor, g/kg	POM, ng/Nm^3	CO, ppm	Nonmethane volatile hydrocarbons, ppm
2.7	11.597	14.4			

Note.—Blanks indicate data not available.

TABLE C-7. EMISSIONS DATA FOR ANTHRACITE COAL COMBUSTION[a] (6)

Run from (6)	Cycle, ON/OFF min	Time segment[b]	Firing rate,[c] lb/hr	Air flow rate, lb/hr Prim.	Air flow rate, lb/hr Sec.	O_2, percent	CO_2, percent	SO_2, ppm	NO, ppm	CO, ppm
9	20/40	1 & 2	67	fan	0	10.0 to 12.6	8.4 to 10.0	200 to 240	30 to 40	150 to >80
		3 & 4	0	0	0	16 to 17	3.3 to 3.7	60 to 100	10 to 15	>1,250 to >1,250
10	50/10	1 & 2	67	fan	0	7 to 10	9.6 to 12.5	240 to 280	60 to 90	50 to 640
		3	0	0	0	13 to 15	6 to 8	130 to 150	30 to 40	>1,250

Run from (6)	Cycle, ON/OFF min	Particulate loading, mg/Nm^3 ON cycle	Particulate loading, mg/Nm^3 OFF cycle	POM loading, mg/Nm^3 ON cycle	POM loading, mg/Nm^3 OFF cycle	Particulate emissions, g/lb coal fed	POM emissions, mg/lb coal fed
9	20/40	73	11	0.12	0.15	0.33	0.86
10	50/10	160	54	0.21	0.11	0.70	0.12

---

[a] Data shown for runs 9 and 10 were combined by MRC to include transient ON and steady-state ON time segments.

[b] 1 - transient ON; 2 - steady-state ON; 3 - transient OFF; 4 - steady-state OFF.

[c] While ON.

On run 1 (6), for example, the air feed rate during the ON segment is 550 lb/hr, the particulate emission factor is 3.9 g/lb over the whole cycle, the particulate loading is 110 mg/Nm^3 during the ON segment and 1,600 mg/Nm^3 during the OFF segment, and the cycle is 20 minutes ON and 40 minutes OFF.

Calculation of the volume of stack gas during each segment is shown below:

For the ON segment:

$$\frac{550\ \text{lb}}{\text{hr}} \times \frac{454\ \text{g}}{\text{lb}} \times \frac{\ell}{1.293\ \text{g}} \times \frac{\text{m}^3}{1{,}000\ \ell} = 193\ \text{m}^3/\text{hr} \ @\ 0°\text{C}$$

$$193\ \text{m}^3 \times \frac{293\ \text{K}}{273\ \text{K}} = 207\ \text{Nm}^3/\text{hr}$$

For the OFF segment, it is first necessary to determine the amount of particulates emitted during each time segment.

For the ON segment:

$$\frac{207\ \text{Nm}^3}{\text{hr}} \times \frac{110\ \text{mg}}{\text{Nm}^3} \times \frac{\text{g}}{1{,}000\ \text{mg}} = 22.8\ \text{g/hr}$$

or:

$$\frac{22.8\ \text{g}}{\text{hr}} \times \frac{\text{hr}}{60\ \text{min}} \times \frac{20\ \text{min}}{\text{cycle}} = 7.6\ \text{g/cycle}$$

Since the overall emission factor is 3.9 g/lb, then:

$$\frac{3.9\ \text{g}}{\text{lb}} \times \frac{42\ \text{lb coal}}{\text{hr}} \times \frac{20\ \text{min}}{60\ \text{min}} = 54.6\ \text{g/cycle}$$

For the OFF segment, the particulates emitted are:

$$54.6\ \text{g/cycle} - 7.6\ \text{g/cycle} = 47.0\ \text{g/cycle}$$

or:

$$\frac{47.0\ \text{g}}{\text{cycle}} \times \frac{\text{cycle}}{40\ \text{min}} \times \frac{60\ \text{min}}{\text{hr}} = 70.5\ \text{g/hr}$$

With this, the volume of flue gas emitted during the OFF segment can be calculated using the corresponding particulate loading:

$$\frac{70.5\ \text{g}}{\text{hr}} \times \frac{\text{Nm}^3}{1{,}600\ \text{mg}} \times \frac{1{,}000\ \text{mg}}{\text{g}} = 44\ \text{Nm}^3/\text{hr}$$

Using these calculated flue gas rates, the emission factors for pollutant gases can be determined, as in the following example for SO_2. Approximately 700 ppm SO_2 in the flue gas during the ON segment and about 390 ppm during the OFF segment were reported (6):

$$0.0007 \times \frac{207\ \text{Nm}^3}{\text{hr}} = 0.145\ \text{Nm}^3/\text{hr of } SO_2$$

and

$$0.00039 \times \frac{44\ \text{Nm}^3}{\text{hr}} = 0.017\ \text{Nm}^3/\text{hr of } SO_2$$

This must be converted to the volume at 0°C to determine the weight of the gas.

$$\frac{0.145\ \text{Nm}^3}{\text{hr}} \times \frac{273\ \text{K}}{293\ \text{K}} = 0.135\ \text{m}^3/\text{hr @ } 0°\text{C}$$

and

$$\frac{0.017\ \text{Nm}^3}{\text{hr}} \times \frac{273\ \text{K}}{293\ \text{K}} = 0.016\ \text{m}^3/\text{hr @ } 0°\text{C}$$

Using the fact that one gram-mole of gas at 0°C occupies 22.4 ℓ of volume, the amount of each gas can be determined as below for SO_2.

For the ON segment:

$$\frac{0.135\ \text{m}^3}{\text{hr}} \times \frac{1{,}000\ \ell}{\text{m}^3} \times \frac{\text{g-mole}}{22.4\ \ell} \times \frac{\text{hr}}{60\ \text{min}} \times \frac{20\ \text{min}}{\text{cycle}} = 2.01\ \text{g-mole/cycle of } SO_2$$

For the OFF segment:

$$\frac{0.017\ \text{m}^3}{\text{hr}} \times \frac{1{,}000\ \ell}{\text{m}^3} \times \frac{\text{g-mole}}{22.4\ \ell} \times \frac{\text{hr}}{60\ \text{min}} \times \frac{40\ \text{min}}{\text{cycle}} = 0.51\ \text{g-mole/cycle of } SO_2$$

Combining for the total cycle, the emission factor can be calculated as follows:

$$\left(\frac{2.01\ \text{g-mole}}{\text{cycle}} + \frac{0.51\ \text{g-mole}}{\text{cycle}}\right) \times \frac{64\ \text{g } SO_2}{\text{g-mole}} \times \frac{\text{cycle}}{14\ \text{lb coal}} \times \frac{\text{lb}}{0.454\ \text{kg}} = 25.4\ \text{g } SO_2/\text{kg coal}$$

Runs 11 and 13 of the study(6) were not used because the calculated flue gas volumes during the ON and OFF phases were nearly identical, and this would not occur under normal operation.

ANTHRACITE COAL COMBUSTION

Emission factors for residential combustion of anthracite coal were obtained from the study(6) discussed under bituminous coal combustion. Like the bituminous runs, the anthracite particulate and POM emission factors were provided in g/lb and mg/lb respectively, while CO, SO_2, and NO were given as concentrations in the flue gas and were listed separately for the ON and OFF segments of the furnace cycle. However, for anthracite test runs, the combustion air flow rate was not measured. Therefore, to obtain the stack gas volume, material balances were made. The carbon balance below is an example.

Assuming that CO_2 and CO concentrations in the air feed are zero,

Carbon in coal = carbon in flue gas as CO_2 and CO

The analysis (6) of the test coal showed 79.4% carbon; for test run 9, the following calculation was performed:

For the ON segment ($CO_2 \simeq 10\%$, $CO \simeq 100$ ppm),

$$\text{Coal}_1 \times 0.794 = V_1 \left[\left(0.1 \times \frac{12}{44} \times \frac{1.98 \text{ kg}}{\text{m}^3}\right) + \left(0.0001 \times \frac{12}{28} \times \frac{1.25 \text{ kg}}{\text{m}^3}\right)\right]$$

or

$$V_1 = 14.7 \text{ Coal}_1 \qquad \text{(C-1)}$$

where V_1 = stack gas volume during ON segment, m^3/hr
Coal_1 = coal burned during ON segment, kg/hr

For the OFF segment, ($CO_2 \simeq 3.3\%$, $CO \simeq 1,300$ ppm),

$$V_1 = 42.9 \text{ Coal}_2 \qquad \text{(C-2)}$$

where V_2 = stack gas volume during OFF segment, m^3/hr
Coal_2 = coal burned during OFF segment, kg/hr

The anthracite feed rate on run 9 was 67 lb/hr or 30.4 kg/hr, and the furnace cycle was 20 min ON/40 min OFF; therefore,

$$\text{Coal}_1 \times \frac{20}{60} + \text{Coal}_2 \times \frac{40}{60} = \frac{30.4 \text{ kg}}{\text{hr}} \times \frac{20}{60}$$

or

$$\text{Coal}_1 + 2\ \text{Coal}_2 = 30.4 \qquad \text{(C-3)}$$

To solve these equations, the ratio of V_1 to V_2 is assumed to be about 4, based on the ratios for bituminous coal. Substituting this into Equation C-1 gives

$$4\ V_2 = 14.7\ \text{Coal}_1$$

Substituting for coal_1, Equation C-3 gives

$$4\ V_2 = 14.7\ (30.4 - 2\ \text{Coal}_2)$$

or

$$\text{Coal}_2 = 15.2 - 0.136\ V_2 \qquad \text{(C-4)}$$

Substituting this into Equation C-2 gives

$$V_2 = 42.9\ (15.2 - 0.136\ V_2)$$

$$V_2 = \frac{95.5\ m^3}{hr}$$

$$V_1 = 4 \times \frac{95.5\ m^3}{hr}$$

$$V_1 = 382\ m^3/hr$$

With values for V_1 and V_2, the procedure for determining emission factors is the same as that used with bituminous coal data (6). The emission factor for hydrocarbons was taken from AP-42 (40).

LIGNITE-FIRED COMBUSTION

No reliable emission data were found on residential combustion of lignite coal; therefore the engineering estimates provided in AP-42 (40) were used for emission factors.

APPENDIX D

POM EMISSION FACTORS FOR VARIOUS FOSSIL-FUELED BOILERS AND FURNACES

Because POM emissions may pose a serious health threat to the general public, the level of POM emissions from residential coal combustion was put into perspective with other fossil-fueled combustion sources of a similar nature. To compare POM emission factors as grams per kilogram of fuel presented a problem when comparing coal-, oil-, and gas-fired combustion processes because the common unit of comparison was based on the heating value of the fuel, or mass emissions of POM per unit of available heat (pg/J)[a]. Data for comparison were obtained from Reference 2 except for residential coal combustion, which data came from this report. Data were converted into the common units of pg/J.

Table 14 in this report presented a POM emission factor of 0.058 g/kg for residential bituminous coal combustion while Table 9 presented an average heating value for bituminous coal of 30 MJ/kg. Therefore:

$$\frac{0.05\ \text{g/kg}}{30\ \text{MJ/kg}} \times \frac{10^{12}\ \text{pg/g}}{10^{6}\ \text{J/MJ}} = 1{,}933\ \text{pg/J}$$

Reference 2 presented a POM emission factor of 885 μg/10^6 Btu for coal-fired utility boilers. Therefore:

$$\frac{885\ \mu\text{g}/10^{6}\ \text{Btu}}{1{,}055\ \text{J/Btu}} \times 10^{6}\ \text{pg}/\mu\text{g} = 0.839\ \text{pg/J}$$

POM emission data for residential gas and oil combustion, commercial/institutional coal combustion, and industrial coal combustion were also presented in Reference 2 but in a somewhat different form. Total annual emissions of POM's in tons per year and total fuel usage in 10^{12} Btu per year were given. This information was converted into emission factors as follows:

$$\frac{\text{ton POM}}{\text{yr}} \times \frac{\text{yr}}{10^{12}\ \text{Btu}} \times \frac{2{,}000\ \text{lb}}{\text{ton}} \times \frac{454 \times 10^{12}\ \text{pg}}{\text{lb}} \times \frac{\text{Btu}}{1{,}055\ \text{J}} = \text{pg/J}$$

The results of these computations are presented in Section 4 of this report.

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[a] picogram per joule; 1 gram = 1 x 10^{12} picograms.

APPENDIX E

DERIVATION OF SOURCE SEVERITY AND AFFECTED POPULATION EQUATIONS

SUMMARY OF SEVERITY EQUATIONS

The severity (S) of pollutants may be calculated using the mass emission rate, Q, the height of the emissions, H, and the ambient air quality standard or the threshold limit value, TLV (54). The equations summarized in Talbe E-1 are developed in detail in this appendix.

TABLE E-1. POLLUTANT SEVERITY EQUATIONS FOR ELEVATED POINT SOURCES

Pollutants	Severity equation
Particulate	$S = \frac{70\ Q}{H^2}$
SO_x	$S = \frac{50\ Q}{H^2}$
NO_x	$S = \frac{315\ Q}{H^{2.1}}$
Hydrocarbon	$S = \frac{162\ Q}{H^2}$
CO	$S = \frac{0.78\ Q}{H^2}$
Other	$S = \frac{5.5\ Q}{TLV \cdot H^2}$

DERIVATION OF χ_{max} FOR USE WITH U.S. AVERAGE CONDITIONS

The most widely accepted formula for predicting downwind ground level concentrations from a point source is (52)

$$\chi = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{(E-1)}$$

where χ = downwind ground level concentration at reference coordinate x and y with emission height of H, g/m³
Q = mass emission rate, g/s
π = 3.14
σ_y = standard deviation of horizontal dispersion, m
σ_z = standard deviation of vertical dispersion, m
u = wind speed, m/s
y = horizontal distance from centerline of dispersion, m
H = height of emission release, m
x = downwind dispersion distance from source of emission release, m

It is assumed that χ_{max} occurs when x is much greater than 0 and y equals 0. For a given stability class, standard deviation of horizontal and vertical dispersion have often been expressed as a function of downwind distance by power law relationships as follows (80):

$$\sigma_y = ax^b \tag{E-2}$$

$$\sigma_z = cx^d + f \tag{E-3}$$

Values for a, b, c, d, and f are given in Tables E-2 and E-3. Substituting these general equations into Equation E-1 yields

$$\chi = \frac{Q}{ac\pi ux^{b+d} + a\pi ufx^b} \exp\left[-\frac{H^2}{2(cx^d + f)^2}\right] \tag{E-4}$$

Assuming that χ_{max} occurs at x less than 100 m or the stability class is C, then f equals 0 and Equation E-4 becomes

$$\chi = \frac{Q}{ac\pi ux^{b+d}} \exp\left[\frac{-H^2}{2c^2x^{2d}}\right] \tag{E-5}$$

For convenience, let

$$A_R = \frac{Q}{ac\pi u} \text{ and } B_R = \frac{-H^2}{2c^2}$$

so that Equation E-5 reduces to

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(80) Martin, D. O., and J. A. Tikvart. A General Atmospheric Diffusion Model for Estimating the Effects on Air Quality of One or More Sources. Presented at the 61st Annual Meeting of the Air Pollution Control Association, St. Paul, Minnesota, June 23-27, 1968. 18 pp.

TABLE E-2. VALUES OF a FOR THE COMPUTATION OF σ_y[a] (81)

Stability class	a
A	0.3658
B	0.2751
C	0.2089
D	0.1471
E	0.1046
F	0.0722

[a] For the equation

$$\sigma_y = ax^b$$

where x = downwind distance
b = 0.9031 (from Reference 82)

TABLE E-3. VALUES OF THE CONSTANTS USED TO ESTIMATE VERTICAL DISPERSION[a] (81)

Usable range, m	Stability class	Coefficient		
		c_1	d_1	f_1
>1,000	A	0.00024	2.094	-9.6
	B	0.055	1.098	2.0
	C	0.113	0.911	0.0
	D	1.26	0.516	-13
	E	6.73	0.305	-34
	F	18.05	0.18	-48.6
		c_2	d_2	f_2
100 to 1,000	A	0.0015	1.941	9.27
	B	0.028	1.149	3.3
	C	0.113	0.911	0.0
	D	0.222	0.725	-1.7
	E	0.211	0.678	-1.3
	F	0.086	0.74	-0.35
		c_3	d_3	f_3
<100	A	0.192	0.936	0
	B	0.156	0.922	0
	C	0.116	0.905	0
	D	0.079	0.881	0
	E	0.063	0.871	0
	F	0.053	0.814	0

[a] For the equation

$$\sigma_z = cx^d + f$$

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(81) Eimutis, E. C., and M. G. Konicek. Derivations of Continuous Functions for the Lateral and Vertical Atmospheric Disperios Coefficients. Atmospheric Environment, 6(11):859-863, 1972.

(82) Tadmor, J., and Y. Gur. Analytical Expressions for the Vertical and Lateral Dispersion Coefficients in Atmospheric Diffusion. Atmospheric Environment, 3(6):688-689, 1969.

$$\chi = A_R x^{-(b+d)} \exp\left[\frac{B_R}{x^{2d}}\right] \tag{E-6}$$

Taking the first derivative of Equation E-6

$$\frac{d\chi}{dx} = A_R \left\{ x^{-b-d} \left(\exp\left[B_R x^{-2d}\right]\right) \left(-2dB_R x^{-2d-1}\right) + \exp\left[B_R x^{-2d}\right] \left(-b-d\right) x^{-b-d-1} \right\} \tag{E-7}$$

and setting this equal to zero (to determine the roots which give the minimum and maximum conditions of χ with respect to x) yields

$$\frac{d\chi}{dx} = 0 = A_R x^{-b-d-1} \left(\exp\left[B_R x^{-2d}\right]\right) \left[-2dB_R x^{-2d} - b - d\right] \tag{E-8}$$

Because it is known that $x \neq 0$ or ∞ at χ_{max}, the following expression must be equal to 0.

$$-2dB_R x^{-2d} - d - b = 0 \tag{E-9}$$

or

$$(b+d) x^{2d} = -2dB_R \tag{E-10}$$

or

$$x^{2d} = \frac{-2dB_R}{b+d} = \frac{2dH^2}{2c^2(b+d)} \tag{E-11}$$

or

$$x^{2d} = \frac{dH^2}{c^2(b+d)} \tag{E-12}$$

or

$$x = \left(\frac{dH^2}{c^2(b+d)}\right)^{\frac{1}{2d}} \text{ at } \chi_{max} \tag{E-13}$$

Thus Equations E-2 and E-3 become

$$\sigma_y = a\left(\frac{dH^2}{c^2(d+b)}\right)^{\frac{b}{2d}} \tag{E-14}$$

$$\sigma_z = c\left(\frac{dH^2}{c^2(b+d)}\right)^{\frac{d}{2d}} = \left(\frac{dH^2}{b+d}\right)^{\frac{1}{2}} \qquad \text{(E-15)}$$

The maximum will be determined for U.S. average conditions of stability. According to Gifford (83), this is when σ_y equals σ_z.

Since b equals 0.9031, and upon inspection of Table E-2 under U.S. average conditions, σ_y equals σ_z, it can be seen that 0.881 is less than or equal to d which is less than or equal to 0.905 (class C stability[a]). Thus, it can be assumed that b is nearly equal to d or

$$\sigma_z = \frac{H}{\sqrt{2}} \qquad \text{(E-16)}$$

and

$$\sigma_y = \frac{a}{c}\,\frac{H}{\sqrt{2}} \qquad \text{(E-17)}$$

Under U.S. average conditions, σ_y equals σ_z and a approximates c if b approximates d and f equals 0 (between class C and D, but closer to belonging in class C).

Then

$$\sigma_y = \frac{H}{\sqrt{2}} \qquad \text{(E-18)}$$

Substituting for σ_y and σ_z into Equation E-1 and letting y equal 0

$$\chi_{max} = \frac{2\ Q}{\pi u H^2} \exp\left[-\frac{1}{2}\left(\frac{H\sqrt{2}}{H}\right)^2\right] \qquad \text{(E-19)}$$

or

$$\chi_{max} = \frac{2\ Q}{\pi e u H^2} \qquad \text{(E-20)}$$

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[a] The values given in Table E-3 are mean values for stability class. Class C stability describes these coefficients and exponents, only within about a factor of two (52).

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(83) Gifford, F. A., Jr. An Outline of Theories of Diffusion in the Lower Layers of the Atmosphere. In: Meteorology and Atomic Energy 1968, Chapter 3, D. A. Slade, ed. Publication No. TID-24190, U.S. Atomic Energy Commission Technical Information Center, Oak Ridge, Tennessee, July 1968. p. 113.

For U.S. average conditions, u equals 4.47 m/s so that Equation E-20 reduces to

$$\chi_{max} = \frac{0.0524\ Q}{H^2} \qquad \text{(E-21)}$$

DEVELOPMENT OF SOURCE SEVERITY EQUATIONS

The general source severity, S, relationship has been defined as follows:

$$S = \frac{\overline{\chi}_{max}}{F} \qquad \text{(E-22)}$$

where $\overline{\chi}_{max}$ = time-averaged maximum ground level concentration
F = hazard factor

Noncriteria Emissions

The value of $\overline{\chi}_{max}$ may be derived from χ_{max}, an undefined "short-term" concentration. An approximation for longer term concentration may be made as follows (52):

For a 24-hr time period,

$$\overline{\chi}_{max} = \chi_{max}\left(\frac{t_o}{t}\right)^{0.17} \qquad \text{(E-23)}$$

or

$$\overline{\chi}_{max} = \chi_{max}\left(\frac{3\ \text{min}}{1{,}440\ \text{min}}\right)^{0.17} \qquad \text{(E-24)}$$

$$\overline{\chi}_{max} = \chi_{max}\ (0.35) \qquad \text{(E-25)}$$

Since the hazard factor is defined and derived from TLV values as follows:

$$F = (\text{TLV})\left(\frac{8}{24}\right)\left(\frac{1}{100}\right) \qquad \text{(E-26)}$$

$$F = (3.33 \times 10^{-3})\ \text{TLV} \qquad \text{(E-27)}$$

then the severity factor, S, is defined as

$$S = \frac{\overline{\chi}_{max}}{F} = \frac{0.35\ \chi_{max}}{(3.33 \times 10^{-3})\ \text{TLV}} \qquad \text{(E-28)}$$

$$S = \frac{105\ \chi_{max}}{TLV} \qquad \text{(E-29)}$$

If a weekly averaging period is used, then

$$\bar{\chi}_{max} = \chi_{max} \left(\frac{3}{10,080}\right)^{0.17} \qquad \text{(E-30)}$$

or

$$\bar{\chi}_{max} = 0.25\ \chi_{max} \qquad \text{(E-31)}$$

and

$$F = (TLV)\left(\frac{40}{168}\right)\left(\frac{1}{100}\right) \qquad \text{(E-32)}$$

$$F = (2.38 \times 10^{-3})TLV \qquad \text{(E-33)}$$

and the severity factor, S, is

$$S = \frac{\bar{\chi}_{max}}{F} = \frac{0.25\ \chi_{max}}{(2.38 \times 10^{-3})TLV} \qquad \text{(E-34)}$$

or

$$S = \frac{105\ \chi_{max}}{TLV} \qquad \text{(E-35)}$$

which is entirely consistent, since the TLV is being corrected for a different exposure period.

Therefore, the severity can be derived from χ_{max} directly without regard to averaging time for noncriteria emissions. Thus, combining Equations E-35 and E-21, for elevated sources, gives

$$S = \frac{5.5\ Q}{TLV \cdot H^2} \qquad \text{(E-36)}$$

Criteria Emissions

For the criteria pollutants, established standards may be used as F values in Equation E-22. These are given in Table E-4 (53).

However, Equation E-23 must be used to give the appropriate averaging period. These equations are developed for elevated sources using Equation E-21.

TABLE E-4. SUMMARY OF NATIONAL AMBIENT AIR QUALITY STANDARDS (53)

Pollutant	Averaging time	Primary standards, $\mu g/m^3$	Secondary standards, $\mu g/m^3$
Particulate matter	Annual (geometric mean)	75	60[a]
	24-hr[b]	260	160
SO_x	Annual (arithmetic mean)	80	60
	24-hr[b]	365	260[c]
	3-hr[b]	-[d]	1,300
CO	8-hr[b]	10,000	10,000
	1-hr[b]	40,000	40,000
Nitrogen dioxide	Annual (arithmetic mean)	100	100
Photochemical oxidants	1-hr[b]	160	160
Hydrocarbons (nonmethane)	3-hr (6 a.m. to 9 a.m.)	160[e]	160

[a] The secondary annual standard (60 $\mu g/m^3$) is a guide for assessing implementation plans to achieve the 24-hr secondary standard.

[b] Not to be exceeded more than once per year.

[c] No standard exists.

[d] The secondary annual standard (260 $\mu g/m^3$) is a guide for assessing implementation plans to achieve the annual standard.

[e] There is no primary ambient air quality standard for hydrocarbons. The value of 160 $\mu g/m^3$ used for hydrocarbons in this report is an EPA-recommended guideline for meeting the primary ambient air quality standard for oxidants.

Carbon Monoxide Severity--

The primary standard for CO is reported for a 1-hr averaging time. Therefore

$$t = 60 \text{ min}$$

$$t_o = 3 \text{ min}$$

$$\bar{\chi}_{max} = \chi_{max}\left(\frac{3}{60}\right)^{0.17} \qquad \text{(E-37)}$$

$$= \frac{2\ Q}{\pi e u H^2}\left(\frac{3}{60}\right)^{0.17} \qquad \text{(E-38)}$$

$$= \frac{2\ Q}{(3.14)(2.72)(4.5)H^2}\ 0.6 \qquad \text{(E-39)}$$

$$\bar{\chi}_{max} = \frac{0.052\ Q}{H^2}\ 0.6 \qquad \text{(E-40)}$$

$$\bar{\chi}_{max} = \frac{(3.12 \times 10^{-2})Q}{H^2} \qquad \text{(E-50)}$$

$$\text{Severity, } S = \frac{\overline{\chi}_{max}}{F} \qquad \text{(E-42)}$$

Setting F equal to the primary standard for CO; i.e., 0.04 g/m^3, yields

$$S = \frac{\overline{\chi}_{max}}{F} = \frac{(3.12 \times 10^{-2})Q}{0.04\ H^2} \qquad \text{(E-43)}$$

or

$$S_{CO} = \frac{0.78\ Q}{H^2} \qquad \text{(E-44)}$$

Hydrocarbon Severity--

The primary standard for hydrocarbon is reported for a 3-hr averaging time.

$$t = 180 \text{ min}$$

$$t_o = 3 \text{ min}$$

$$\overline{\chi}_{max} = \chi_{max} \left(\frac{3}{180}\right)^{0.17} \qquad \text{(E-45)}$$

$$= 0.5\chi_{max} \qquad \text{(E-46)}$$

$$= \frac{(0.5)(0.052)Q}{H^2} \qquad \text{(E-47)}$$

$$\overline{\chi}_{max} = \frac{0.026\ Q}{H^2} \qquad \text{(E-48)}$$

For hydrocarbons, the concentration of 1.6 x 10^{-4} g/m^3 has been issued as a guideline for achieving oxidant standards. Therefore,

$$S = \frac{\overline{\chi}_{max}}{F} = \frac{0.026\ Q}{1.6 \times 10^{-4}\ H^2} \qquad \text{(E-49)}$$

or

$$S_{HC} = \frac{162.5\ Q}{H^2} \qquad \text{(E-50)}$$

Particulate Severity--

The primary standard for particulate is reported for a 24-hr averaging time.

$$\overline{\chi}_{max} = \chi_{max}\left(\frac{3}{1,440}\right)^{0.17} \quad \text{(E-51)}$$

$$= \frac{(0.05)(0.052)Q}{H^2} \quad \text{(E-52)}$$

$$\overline{\chi}_{max} = \frac{0.0182\ Q}{H^2} \quad \text{(E-53)}$$

For particulates, $F = 2.6 \times 10^{-4}$ g/m^3, and

$$S = \frac{\overline{\chi}_{max}}{F} = \frac{0.0182\ Q}{(2.6 \times 10^{-4})H^2} \quad \text{(E-54)}$$

$$S_P = \frac{70\ Q}{H^2} \quad \text{(E-55)}$$

SO_x Severity--
The primary standard for SO_x is reported for a 24-hr averaging time.

$$\overline{\chi}_{max} = \frac{0.0182\ Q}{H^2} \quad \text{(E-56)}$$

The primary standard is 3.65×10^{-4} g/m^3. Therefore,

$$S = \frac{\overline{\chi}_{max}}{F} = \frac{0.0182\ Q}{(3.65 \times 10^{-4})H^2} \quad \text{(E-57)}$$

or

$$S_{SO_x} = \frac{50\ Q}{H^2} \quad \text{(E-58)}$$

NO_x Severity--
Since NO_x has a primary standard with a 1-yr averaging time, the χ_{max} correction equation cannot be used. As an alternative, the following equation is used:

$$\overline{\chi} = \frac{2.03\ Q}{\sigma_z u x} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad \text{(E-59)}$$

A difficulty arises, however, because a distance x, from emission point to receptor, is included; hence, the following rationale is used:

$$\chi_{max} = \frac{2\ Q}{\pi e u H^2}$$

is valid for neutral conditions or when σ_z equals σ_y. This maximum occurs when

$$H = \sqrt{2}\sigma_z$$

and since, under these conditions,

$$\sigma_z = ax^b$$

then the distance, x_{max}, where the maximum concentration occurs is

$$x_{max} = \left(\frac{H}{\sqrt{2}a}\right)^{\frac{1}{b}}$$

For class C conditions,

$$a = 0.113$$

$$b = 0.911$$

Simplifying Equation E-59,

$$\sigma_z = 0.113\ x_{max}^{0.911}$$

and

$$u = 4.5\ m/s$$

Letting $x = x_{max}$ in Equation E-59,

$$\overline{\chi}_{max} = \frac{4\ Q}{x_{max}^{1.911}} \exp\left[-\ \frac{1}{2}\ \left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{(E-60)}$$

where

$$x_{max} = \left(\frac{H}{0.16}\right)^{1.098} \qquad \text{(E-61)}$$

$$x_{max} = 7.5\ H^{1.098} \qquad \text{(E-62)}$$

and

$$\frac{4\ Q}{x_{max}^{1.911}} = \frac{4\ Q}{(7.5\ H^{1.098})^{1.911}} \qquad \text{(E-63)}$$

Therefore,

$$\bar{\chi}_{max} = \frac{0.085\ Q}{H^{2.1}} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \tag{E-64}$$

As noted above,

$$\sigma_z = 0.113\ x^{0.911} \tag{E-65}$$

$$\sigma_z = 0.113(7.5\ H^{1.1})^{0.911} \tag{E-66}$$

or

$$\sigma_z = 0.71\ H \tag{E-67}$$

Therefore,

$$\bar{\chi}_{max} = \frac{0.085\ Q}{H^{2.1}} \exp\left[-\frac{1}{2}\left(\frac{H}{0.71\ H}\right)^2\right] \tag{E-68}$$

$$= \frac{0.085\ Q}{H^{2.1}}\ (0.371) \tag{E-69}$$

$$\bar{\chi}_{max} = \frac{3.15 \times 10^{-2}\ Q}{H^{2.1}} \tag{E-70}$$

Since the NO_x standard is 1.0 x 10^{-4} g/m^3, the NO_x severity equation is

$$S_{NO_x} = \frac{(3.15 \times 10^{-2})Q}{1 \times 10^{-4}\ H^{2.1}} \tag{E-71}$$

$$S_{NO_x} = \frac{315\ Q}{H^{2.1}} \tag{E-72}$$

AFFECTED POPULATION CALCULATION

Another form of the plume dispersion equation is needed to calculate the affected population since the population is assumed to be distributed uniformly around the source. If the wind directions are taken to 16 points and it is assumed that the wind directions within each sector are distributed randomly over a period of a month or a season, it can be assumed that the effluent is uniformly distributed in the horizontal within the sector. The appropriate equation for average concentration $(\bar{\chi})$ is then:

$$\overline{\chi} = \frac{2.03\ Q}{\sigma_z u x} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \text{ (g/m}^3\text{)} \qquad \text{(E-73)}$$

To find the distances at which $\overline{\chi}/F = 0.1$, roots are determined for the following equation:

$$0 = \left\{\frac{2.03\ Q}{F\sigma_z u x} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]\right\} - 0.1 \qquad \text{(E-74)}$$

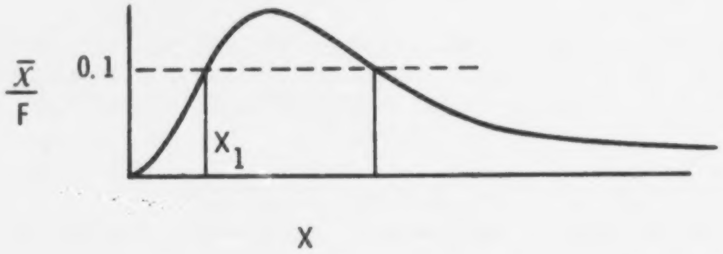
keeping in mind that:

$$\sigma_z = a\ x^b + c$$

where a, b, and c are functions of atmospheric stability and are assumed to be for stability Class C.

Since equation E-74 is a transcendental equation, the roots are found by an iterative technique using the computer.

For a specified emission from a typical source, $\overline{\chi}/F$ as a function of distance might look as follows:



The affected population is then in the area

$$A = \pi(X_2^2 - X_1^2) \qquad \text{(E-75)}$$

If the affected population density is D_p, then the total affected population, P, is

$$P = D_p A \text{ (persons)} \qquad \text{(E-76)}$$

APPENDIX F

TOTAL COAL-FIRED RESIDENTIAL COMBUSTION EMISSIONS

Total criteria emissions from coal-fired residential combustion equipment were compared on state and national bases to emissions from all stationary sources. State emissions were calculated by multiplying the emission factors presented in Section 4 by the estimated fuel usage in each state for each source. In the case of bituminous coal state emissions were determined by weighting an emission factor to represent the distribution of automatic and hand-fed heating equipment. Table B-2 in Appendix B shows that 60% of residential heating takes place in furnaces and boilers that are assumed to be automatic devices. The emission factor for hand-fed units was determined from Table 16 in Section 4. Table F-1 shows the emission factors for automatic and hand-fed equipment and the average emission factor weighted by percent automatic and hand-fed equipment.

TABLE F-1. WEIGHTED AVERAGE EMISSION FACTORS FOR CRITERIA POLLUTANTS FROM BITUMINOUS COAL-FIRED RESIDENTIAL COMBUSTION UNITS (g/kg)

Emission species	Automatic equipment (60%)	Hand-fed equipment (40%)	Weighted average
Particulate	5.1	13	8.3
SO_x	15.0S	16.0S	15.5S
NO_x	3.9	1.6	3.0
Hydrocarbon	1.8	5	3.1
CO	13.0	50.0	28.0

State emissions of SO_x from residential bituminous coal combustion were determined by using the average sulfur content of the coal most likely to be used by the residential sector in each state. Coal origin and sulfur content are presented by state in Table F-2. Tables F-3, F-4, and F-5 give the criteria emissions and emission ratios by state and on a national level for each source. Total state emissions were taken from the NEDS inventory (84) which is shown in Table F-6.

TABLE F-2. ORIGIN OF RESIDENTIAL BITUMINOUS COAL AND SULFUR CONTENT[a]

State	Region of coal origin (20, 26)	Average sulfur content (20), %
Alabama	GP	1.9
Alaska	AL	0.2
Arizona	RM	0.6
Arkansas	IP	3.9
California	RM	0.6
Colorado	RM	0.6
District of Columbia	A	2.3
Florida	GP	1.9
Georgia	A	2.3
Hawaii	PC	0.4
Idaho	RM	0.6
Illinois	IP	3.9
Indiana	IP	3.9
Iowa	IP	3.9
Kansas	IP	3.9
Kentucky	A	2.3
Louisiana	GP	1.9
Massachusetts	A	2.3
Michigan	A	2.3
Minnesota	IP	3.9
Mississippi	GP	1.9
Missouri	IP	3.9
Montana	NGP	1.2
Nebraska	IP	3.9
Nevada	RM	0.6
New Mexico	RM	0.6
New York	A	2.3
North Carolina	A	2.3
Ohio	A	2.3
Oklahoma	IP	3.9
Oregon	PC	0.4
Pennsylvania	A	2.3
South Carolina	A	2.3
South Dakota	NGP	1.2
Tennessee	A	2.3
Texas	IP	3.9
Utah	RM	0.6
Virginia	A	2.3
Washington	PC	0.4
West Virginia	A	2.3
Wisconsin	A	2.3
Wyoming	RM	0.6

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[a] Abbreviations used: A - Appalachain Region; AL - Alaska; GP - Gulf Province; IP - Interior Province; NGP - Northern Great Plains Province/ PC - Pacific Coast Province; RM - Rocky Mountain Province.

TABLE F-3. STATE-BY-STATE LISTING OF RESIDENTIAL BITUMINOUS COAL-FIRED EMISSIONS

State	Fuel usage, metric tons/yr	Metric tons					Percent of total state emissions				
		Particulates	SO_x	NO_x	Hydrocarbons	CO	Particulates	SO_x	NO_x	Hydrocarbons	CO
Alabama	61,264	507	1,806	183	189	1,686	0.04	0.2	0.05	0.03	0.1
Alaska	6,222	51	19	18	19	172	0.3	0.3	0.06	0.06	0.1
Arizona	363	3.0	3.4	1.1	1.1	10	<0.01	<0.01	<0.01	<0.01	<0.01
Arkansas	4,461	37	270	13	13	123	0.03	0.7	<0.01	<0.01	0.01
California	1,667	14	16	5.0	5.1	45	<0.01	<0.01	<0.01	<0.01	<0.01
Colorado	21,782	180	203	65	67	599	0.1	0.4	0.04	0.03	0.06
District of Columbia	16,221	134	579	48	50	447	0.6	1.0	0.08	0.2	0.2
Florida	176	1.6	5.2	0.5	0.6	4.9	<0.01	<0.01	<0.01	<0.01	<0.01
Georgia	8,118	67	290	24	25	224	0.02	0.06	<0.01	<0.01	<0.01
Hawaii	15	0.1	0.1	0.04	0.05	0.5	<0.01	<0.01	<0.01	<0.01	<0.01
Idaho	23,125	191	215	69	71	637	0.3	0.4	0.2	0.1	0.2
Illinois	216,670	1,792	13,114	647	668	5,967	0.2	0.7	0.07	0.04	0.1
Indiana	28,547	235	1,728	85	88	786	0.03	0.09	<0.01	0.02	0.03
Iowa	10,322	86	625	31	32	284	0.03	0.2	0.02	0.01	0.02
Kansas	869	8.0	52	2.6	2.7	24	<0.01	0.06	<0.01	<0.01	<0.01
Kentucky	242,317	2,003	8,649	724	747	6,673	0.3	0.7	0.2	0.2	0.5
Louisiana	66	0.5	1.9	0.2	0.2	1.8	<0.01	<0.01	<0.01	<0.01	<0.01
Massachusetts	4,278	35	152	12	13	118	0.03	0.02	<0.01	<0.01	<0.01
Michigan	22,448	186	801	67	70	619	0.03	0.06	<0.01	0.01	0.02
Minnesota	26,050	215	1,577	78	81	718	0.08	0.4	0.02	0.02	0.05
Mississippi	5,453	46	161	17	17	151	0.03	0.3	<0.01	0.01	0.02
Missouri	7,021	59	425	21	21	193	0.03	0.04	<0.01	<0.01	<0.01
Montana	8,785	73	164	27	27	241	0.03	0.02	0.02	0.01	0.03
Nebraska	1,897	16	114	5.6	5.8	52	0.02	0.2	<0.01	<0.01	<0.01
Nevada	1,112	9.5	11	3.3	3.4	31	0.01	<0.01	<0.01	<0.01	<0.01
New Mexico	1,207	9.5	12	3.6	3.7	34	<0.01	<0.01	<0.01	<0.01	<0.01
New York	1,663	14	59	5.0	5.1	45	<0.01	0.02	<0.01	<0.01	<0.01
North Carolina	69,434	574	2,478	208	214	1,912	0.1	0.5	0.05	0.05	0.1
Ohio	60,185	498	2,149	180	186	1,657	0.03	0.07	0.02	0.02	0.03
Oklahoma	758	5.4	46	2.2	2.4	21	<0.01	0.04	<0.01	<0.01	<0.01
Oregon	2,772	22	17	8.3	8.7	76	0.01	0.05	<0.01	<0.01	<0.01
Pennsylvania	216,528	1,790	7,729	647	667	5,963	0.1	0.3	0.02	0.07	0.2
South Carolina	25,932	215	925	77	80	714	0.1	0.4	0.02	0.01	0.02
South Dakota	4,405	37	82	13	13	122	0.6	0.5	0.02	0.02	0.03
Tennessee	220,007	1,819	7,853	657	678	6,059	0.4	0.7	0.2	0.2	0.4
Texas	365	3.2	22	1.1	1.1	10	<0.01	<0.01	<0.01	<0.01	<0.01
Utah	29,427	243	274	88	91	810	0.3	0.18	0.1	0.1	0.2
Virginia	166,946	1,380	5,960	499	514	4,598	0.3	1.4	0.1	0.1	0.3
Washington	10,945	91	68	32	34	301	0.06	0.03	0.02	0.01	0.02
West Virginia	185,318	1,533	6,615	554	571	5,103	0.7	1.0	0.2	0.5	1.0
Wisconsin	21,332	176	761	64	66	588	0.5	0.1	0.02	0.02	0.03
Wyoming	7,683	64	72	23	24	212	0.08	0.1	0.04	0.04	0.06
Total	1,744,156	14,425	66,104	5,210	5,376	58,032	0.08	0.2	0.02	0.02	0.05

TABLE F-4. STATE-BY-STATE LISTING OF RESIDENTIAL ANTHRACITE-FIRED EMISSIONS

State	Fuel usage, metric tons/yr	Metric tons					Percent of total state emissions				
		Partic- ulates	SO_x	NO_x	Hydro- carbons	CO	Partic- ulates	SO_x	NO_x	Hydro- carbons	CO
Connecticut	5,644	6	45	5	7	47	<0.1	<0.1	<0.1	<0.1	<0.1
Delaware	3,690	4	30	3	5	32	<0.1	<0.1	<0.1	<0.1	<0.1
District of Columbia	2,195	2	17	2	3	18	<0.1	<0.1	<0.1	<0.1	<0.1
Illinois	4,462	5	36	4	6	37	<0.1	<0.1	<0.1	<0.1	<0.1
Indiana	6,972	8	57	6	9	58	<0.1	<0.1	<0.1	<0.1	<0.1
Maine	1,783	2	14	1	2	15	<0.1	<0.1	<0.1	<0.1	<0.1
Maryland	48,285	53	391	44	63	401	<0.1	0.1	<0.1	<0.1	<0.1
Massachusetts	14,693	16	119	14	19	122	<0.1	<0.1	<0.1	<0.1	<0.1
Michigan	7,701	8	62	7	10	64	<0.1	<0.1	<0.1	<0.1	<0.1
New Hampshire	942	1	7	1	1	8	<0.1	<0.1	<0.1	<0.1	<0.1
New Jersey	63,140	69	511	57	82	525	<0.1	0.1	<0.1	<0.1	<0.1
New York	132,246	145	1,072	119	172	1,098	<0.1	0.3	<0.1	<0.1	<0.1
Ohio	6,517	7	53	6	8	54	<0.1	<0.1	<0.1	<0.1	<0.1
Pennsylvania	552,942	608	4,478	498	719	4,593	<0.1	0.1	<0.1	<0.1	0.1
Rhode Island	932	1	7	1	1	8	<0.1	<0.1	<0.1	<0.1	<0.1
Vermont	2,057	2	17	2	3	17	<0.1	0.1	<0.1	<0.1	<0.1
							Percent of U.S. Emissions				
Total	854,201	937	6,916	769	1,110	7,089	<0.01	0.02	<0.01	<0.01	0.01

TABLE F-5. LIGNITE-FIRED EMISSIONS IN NORTH DAKOTA[a]

Emission species	Metric tons	Percent of total state emissions	Percent of U.S. emissions
Particulates	244	0.3	<0.01
SO_x	423	0.5	<0.01
NO_x	56	<0.1	<0.01
Hydrocarbons	9	<0.1	<0.01
CO	19	<0.1	<0.01

[a] Based on fuel usage of 18,784 metric tons/yr.

TABLE F-6. NEDS EMISSION SUMMARY BY STATE (84)
(metric tons)

State	Particulates	SO_x	NO_x	Hydrocarbons	CO
Alabama	1,178,643	882,731	397,068	643,410	1,885,657
Alaska	13,913	5,874	32,757	28,389	167,357
Arizona	72,685	1,679,768	[illegible]3,871	189,981	815,454
Arkansas	137,817	39,923	1[illegible],989	195,538	843,204
California	1,006,452	393,326	1,663,139	2,160,710	8,237,667
Colorado	201,166	49,188	147,496	193,456	875,781
Connecticut	40,074	168,068	155,832	219,661	897,580
Delaware	36,808	209,310	58,407	63,886	204,227
Dist. Columbia	19,451	60,630	46,824	41,789	190,834
Florida	226,460	897,381	644,794	619,872	2,695,817
Georgia	404,574	472,418	369,817	458,010	2,036,010
Hawaii	61,621	45,981	44,221	89,530	275,566
Idaho	55,499	54,387	48,552	84,230	343,720
Illinois	1,143,027	2,043,020	974,372	1,825,913	6,412,718
Indiana	748,405	2,050,541	1,371,233	600,477	2,933,780
Iowa	216,493	283,416	242,524	316,617	1,440,621
Kansas	348,351	86,974	233,987	309,633	1,002,375
Kentucky	546,214	1,202,827	419,142	326,265	1,189,932
Louisiana	380,551	166,664	442,817	1,919,662	5,633,827
Maine	49,155	144,887	76,741	122,918	376,196
Maryland	494,921	420,037	265,204	295,867	1,261,804
Massachusetts	96,160	636,466	334,379	440,481	1,682,218
Michigan	705,921	1,466,935	2,222,438	717,891	3,243,526
Minnesota	266,230	391,633	311,834	410,674	1,760,749
Mississippi	168,355	50,591	172,519	195,950	829,094
Missouri	202,435	1,152,373	448,300	413,130	1,854,901
Montana	272,688	871,235	148,405	271,824	611,061
Nebraska	95,338	58,014	101,948	127,821	569,522
Nevada	94,040	304,851	88,933	53,673	215,751
New Hampshire	14,920	86,596	67,309	88,469	256,380
New Jersey	151,768	463,736	489,216	819,482	2,877,319
New Mexico	102,785	444,310	199,181	152,057	504,249
New York	160,044	345,979	572,451	1,262,206	4,881,922
North Carolina	481,017	473,020	412,599	447,238	1,734,398
North Dakota	78,978	78,537	85,708	70,289	318,679
Ohio	1,766,056	2,980,333	1,101,470	1,153,493	5,205,719
Oklahoma	93,595	130,705	222,687	341,358	1,456,627
Oregon	169,449	36,776	135,748	234,669	929,247
Pennsylvania	1,810,598	2,929,137	3,017,345	891,763	3,729,830
Rhode Island	13,073	65,761	46,921	65,833	283,650
South Carolina	198,767	247,833	521,544	907,833	4,222,168
South Dakota	52,336	17,354	49,490	90,478	387,356
Tennessee	409,704	1,179,982	426,454	362,928	1,469,253
Texas	549,399	753,098	1,303,801	2,218,891	6,897,748
Utah	71,692	152,526	80,998	98,282	402,527
Vermont	14,587	17,751	24,286	41,980	150,510
Virginia	477,494	447,394	329,308	369,416	1,548,031
Washington	161,934	272,991	187,923	344,643	1,659,117
West Virginia	213,715	678,348	229,598	116,155	494,214
Wisconsin	411,558	712,393	408,525	523,930	1,582,869
Wyoming	75,427	69,394	72,572	55,319	303,297

ADJUSTMENTS TO GRAND TOTAL

The United States summary does not include certain source categories. The following additions should be considered part of the United States grand total for a more accurate picture of nationwide emissions.

New York pt. sources	311,000	993,000	382,000	127,000	44,000
Forest wild fires	375,000	0	88,000	529,000	3,089,000
Agricultural burning	272,000	15,000	29,000	272,000	1,451,000
Structural fires	52,000	0	6,000	61,000	200,000
Coal refuse piles	100,000	128,000	31,000	62,000	308,000
Total	1,110,000	1,076,000	536,000	1,051,000	5,086,000
U.S. subtotal (above)	16,762,000	28,873,000	21,722,000	23,994,000	91,782,000
U.S. grand total	17,872,000	29,949,000	22,258,000	25,045,000	96,868,000

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(84) 1972 National Emissions Report; National Emissions Data System (NEDS) of the Aerometric and Emissions Reporting System (AEROS). EPA-450/2-74-012, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1974. 422 pp.

GLOSSARY

affected population: Number of persons around a representative source who are exposed to a source severity greater than 0.1 or 1.0 as specified.

anthracite: Dense hard coal with a very high percentage of fixed carbon, usually about 90%. Most anthracite is mined in Pennsylvania.

barometric damper: Balanced butterfly gate located outside the flue gas flow on an exhaust stack in a tee fitting. It is used to control draft.

bituminous: Coal covering a wide range of properties, but in general with a fixed carbon content under 80% and volatile matter over 20%.

boiler: Closed vessel in which fuel is burned to generate steam or heat water.

blow holes: Holes formed in a caked fuel bed from the force of mechanically delivered combustion air.

caking coals: Coals that fuse and lose their shape during combustion. The degree of caking is measured by the free swelling index.

clinker: Fused mass of the residue (ash) from coal combustion.

criteria emissions: Those for which air quality standards have been established.

cycle: Pattern of operation of automatic heating equipment characterized by four segments; initial ON, steady-state ON, initial OFF, and steady-state OFF.

damper: Valve or place used to regulate the flow of air to a combustion process.

degree day: Unit representing a one degree Fahrenheit departure below 65°F in the mean outdoor temperature for one day.

draft: Gas flow resulting from the pressure difference between the combustion unit and the atmosphere, which moves the products of combustion from the combustion unit to the atmosphere. 1) Natural: the negative pressure created by the difference in density between the hot flue gases and the atmosphere. 2) Induced: the negative pressure created by the action of a fan, blower, or ejector which is located between the combustion unit and the stack. 3) Forced: the positive pressure created by the action of a fan or blower, which supplies the primary or secondary air.

emission factor: Quantify of emissions per quantity of mass burned.

free swelling index: Measure of the caking properties of coal determined by the volume change in coal during its plastic stage.

flue: Enclosed passage for conveying combustion gases to the atmosphere.

heating value: Amount of heat produced by combustion of a unit quantity of solid or liquid fuel; determined in the laboratory at constant volume in an oxygen bomb calorimeter.

housing unit: Apartment, house, group of rooms, or a single room occupied or intended for occupancy as separate living quarters.

lignite: Brown, noncaking woody coal with high moisture and low heating value. It is usually mined in Texas and North Dakota.

national emission burden: Ratio of annual emissions from a specific source to the total national emissions from all stationary sources.

overfeed: Method of feeding solid fuel to a fuel bed where the fresh fuel is charged to the top of the fuel bed.

overfire: Portion of the combustion air which enters the combustion zone over the fuel bed to provide turbulence for smoke reduction in hand- and stoker-fed coal combustion equipment.

plenum: Air space or chamber under pressure.

proximate analysis: Fuel analysis on the basis of percent fixed carbon, volatile matter, moisture, and ash.

pyrolysis: Chemical decomposition by the application of heat.

rank of coal: Method of classifying coal by chemical and physical properties.

representative source: Coal-fired residential combustion source defined for use in calculating source severity.

retort: Cast iron chamber in the shape of a cup or trough used to devolatilize and ignite coal in a stoker-fed furnace or boiler.

stoker: Mechanical device used to feed solid fuel to a combustion unit.

source severity: Indication of the hazard potential of an emission source.

state emission burden: Ratio of annual emissions from a specific source in any state to the total state emissions from all stationary sources.

threshold limit value (TLV): Refers to airborne concentrations of substances and represents conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect.

tuyeres: Slotted holes in the retort for directing combustion air to the fuel bed of a coal-fired heating device.

ultimate analysis: Fuel analysis on the basis of elemental content; namely, carbon, hydrogen, oxygen, nitrogen, sulfur, and ash.

underfeed: Method of feeding solid fuel to a fuel bed where the fresh fuel is introduced from beneath the fuel bed.

underfire: Method of providing combustion air to a fuel bed by forcing the air through the fuel bed from underneath.

warm-air furnace: Closed vessel in which fuel is burned to heat room air.

wind box: Enclosure around a stoker which directs combustion air through the retort.

worm-feed mechanism: Motor-driven screw which conveys solid fuel from storage and discharges the fuel into the retort of a combustion operation.

CONVERSION FACTORS AND METRIC PREFIXES (85)

CONVERSION FACTORS

To convert from	To	Multiply by
Degree Celsium (°C)	Degree Fahrenheit (°F)	$t_{°F} = 1.8\ t_{°C} + 32$
Kelvin (K)	Degree Celsius (°C)	$t_{°C} = t_K - 273.15$
Gram (g)	Pound-mass	2.205×10^{-3}
Gram/second (g/s)	Pounds/hour	7.930
Joule (J)	British thermal unit (Btu)	9.479×10^{-4}
Kilogram (kg)	Pound mass (lb mass avoirdupois)	2.204
Kilogram (kg)	Ton (short, 2,000 lb mass)	1.102×10^{-3}
Kilogram/meter^3 (kg/m^3)	Lb mass/foot^3	6.243×10^{-2}
Kilometer^2 (km^2)	Mile^2	2.591
Meter (m)	Foot	3.281
Meter (m)	Inch	3.937×10^1
Meter^3 (m^3)	Foot^3	3.531×10^1
Metric ton	Pound-mass	2.205×10^3
Pascal (Pa)	Pound-force/inch^2 (psi)	1.450×10^{-4}

METRIC PREFIXES

Prefix	Symbol	Multiplication factor	Example
Giga	G	10^9	1 Gg = 1 x 10^9 grams
Mega	M	10^6	1 MJ = 1 x 10^6 joules
Kilo	k	10^3	1 kPa = 1 x 10^3 pascals
Milli	m	10^{-3}	1 mg = 1 x 10^{-3} gram
Micro	µ	10^{-6}	1 µm = 1 x 10^{-6} meter
Pico	p	10^{-12}	1 pg = 1 x 10^{-12} gram

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(85) Metric Practice Guide. ASTM Designation E 380-74, American Society for Testing and Materials, Philadelphia, Pennsylvania, November 1974. 34 pp.